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**SOLID-PROPELLANT ROCKET IGNITION
SYSTEMS**

**IV. EVALUATION OF THE NOL "HI-LO"
(ROCKET-IN-ROCKET) IGNITER**

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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SOLID-PROPELLANT ROCKET IGNITION SYSTEMS
IV. EVALUATION OF THE NOL "HI-LO" (ROCKET-IN-ROCKET) IGNITER

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ABSTRACT: A study is made of the performance of a small, mono-vent rocket ("Hi-Lo") used as an igniter in the NOL ignition research program. Described are the theoretical and experimental methods used to predict the transient internal ballistics of the igniter and to define the physical-chemical and hydrodynamic characteristics of the igniter output. The output parameters evaluated are the rates and quantities of mass and thermal energy discharged from the igniter during a shot and the velocity and flame pattern of the vented igniter products. Emphasis is placed on the study of igniter performance resulting from the use of M2 igniter pellets (small cylinders of double-base composition).

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The work reported here was carried out under Task RMMP-22064/212-1/F009-06-04, G/M Ignition Research. A vital part of a scientific study of solid-rocket ignition is a quantitative characterization of the ignition-energy source. This report treats a performance evaluation made of a rocket-type ignition system called the "Hi-Lo" igniter, that is used to ignite the NOL ignition-research rocket. A description is given of the techniques that can be used to predict the internal ballistics and what are believed to be important output parameters of the igniter.

R. E. ODENING

Albert Lightbody
ALBERT LIGHTBODY
By direction

LIST OF SYMBOLS

Part I - Symbols in Roman Lettering

a	= linear burning-rate coefficient
A_E	= nozzle exit area
A_t	= nozzle throat area
B	= coefficient constant in empirical ballistic correlation (Eq. (12))
b	= exponent constant in empirical ballistic correlation (Eq. (12))
C_D	= nozzle discharge coefficient
c_p	= specific heat capacity at constant pressure
D	= diameter
D_0	= initial pellet diameter
h_C	= specific enthalpy in the igniter combustion chamber
h_E	= specific enthalpy at nozzle exit conditions
I	= impetus
K	= ratio of pellet surface to nozzle throat area
L	= length
L_0	= initial pellet length
M_E	= quantity of igniter mass vented from the igniter
M_0	= initial charge weight of ignition material
$m(t)$	= change in the quantity of igniter output with time
Δm	= incremental change in the quantity of igniter output
\dot{m}_E	= rate of venting of igniter output
M.W.	= molecular weight of combustion products

LIST OF SYMBOLS (Cont'd)

N	= number of ignition material pellets
n	= linear burning-rate exponent
P	= pressure
P_C	= combustion chamber pressure
$(P_C)_{\max}$	= maximum igniter chamber pressure
P_E	= pressure of igniter products at nozzle exit conditions
P_g	= gas static pressure in non-vent vessel
q_E	= quantity of thermal energy vented from the igniter
\dot{q}_E	= rate of venting of thermal energy from the igniter
R	= universal gas constant
r	= linear burning rate
S	= burning surface of propellant or ignition material
S_0	= initial burning surface of ignition material
T_C	= combustion chamber temperature
T_E	= temperature of igniter products at nozzle exit conditions
T_b	= reference temperature
T_g	= gas static temperature in non-vent vessel
T_s	= surface temperature
t	= time
V	= volume of non-vent vessel
V_C	= igniter chamber volume (empty)
V_F	= igniter free volume (loaded)
$(V_F)_0$	= initial free volume in igniter
v_E	= exit velocity of igniter output

LIST OF SYMBOLS (Cont'd)

X = distance burned

Part II - Symbols in Greek Lettering

γ = specific heat ratio

Δ = packing density

η = co-volume

ρ_p = density of ignition material

τ = time interval

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I. INTRODUCTION

A. BACKGROUND

The objective of the NOL ignition research program is to provide design criteria for solid-rocket igniters. The program is based on a scientific study of the physical-chemical and hydrodynamic phenomena that take place when a rocket is ignited by a rocket-in-rocket type ignition system. The plan of the program is to make theoretical and experimental studies of:

1. The igniter performance (the internal ballistics and venting of mass and energy).
2. The distribution of the igniter output in a rocket motor and the absorption of the energy by the propellant grain.
3. The ignition characteristics of the rocket propellant exposed to the igniter output.

It is hoped that an understanding of these processes, and the interrelations among them, will result in engineering-type correlations that will describe the function of the igniter in ignition and thus lead to igniter-design criteria.

Before a practical scientific study of rocket ignition is possible it is necessary to have a realistic ignition system of predictable performance. In the past, some of the devices that have been used as igniters by various researchers are: the arc-image (3,4), the locked-stroke (adiabatic) compressor (5,7), the shock-tube (6,14), and the rocket-in-rocket system - a small rocket used to ignite a larger rocket (8,11,19).

In the NOL ignition work, a type of rocket-in-rocket ignition system called the "Hi-Lo" igniter is used. This igniter derives its name from the fact that its chamber pressure remains higher than that in the rocket to be ignited during all or part of the ignition interval; that is, the period when the rocket is approaching its equilibrium chamber pressure. The igniter can best be described as a small mono-vent rocket that uses propellant or pyrotechnic pellets as ignition material.

To date, the emphasis of the research has been on the evaluation of the performance of the "Hi-Lo" igniter. The methods used for this evaluation and the progress made in characterizing the igniter performance are the topics of this report.

The "Hi-Lo" igniter was chosen for the NOL program because it offers several advantages:

1. Ignition energy can be supplied to a rocket under the wide variety of thermodynamic and hydrodynamic conditions needed for a comprehensive and realistic study of the ignition phenomenon.
2. Many of the ballistic equations used to describe large-rocket performance can also be used to predict the igniter internal ballistics and output.
3. The pressurization of the igniter can be made independent of the rocket pressurization over the ignition interval by a proper choice of the internal-ballistic parameters of the igniter.
4. The operation of the igniter during the ignition interval is such that the most efficient use of the igniter output by the rocket grain can be realized. This is so because the igniter delivers its output at a maximum rate when the grain is most receptive and at a decreasing rate when the motor is approaching its operating pressure.
5. Rocket-in-rocket igniters have been used successfully for the ignition of in-service rockets. Thus, the use of a practical ignition system in the ignition research program provides a direct and immediate application of the research results to the design of operational igniters.

One disadvantage of using the "Hi-Lo" igniter as a research tool, however, is that the pressurization of the igniter by the ignition-material combustion products is a completely transient process. This is the result of the short duration of the combustion process, heat losses, the regressive-burning characteristics of the ignition pellets, and to a lesser extent, the change in the combustion-chamber free volume as the igniter pellets burn. The end result of this transient behavior is that the internal-ballistic equations used with large, long-burning rockets must be modified, or at least carefully evaluated, before they can be applied to an analysis of the "Hi-Lo" igniter performance. This is particularly true if the ignition material used produces significant amounts of non-gaseous combustion products.

B. DESCRIPTION OF THE "HI-LO" IGNITER

The general design characteristics of the NOL "Hi-Lo" igniter are illustrated in a photograph (Fig. 1) and a cross-sectional view (Fig. 2). The basic design features are: a small, barrel-shaped combustion chamber (maximum volume of 20cc); a De Laval nozzle (with variable throat and exit areas); a ceramic-coated screen between the combustion chamber and the convergent section of the nozzle (to prevent pellets from "blowing out" of the chamber); and electrodes to conduct electric current to an exploding bridge wire, squib or "electric match" used to ignite the pellets in the chamber. The igniter is designed to withstand a maximum pressure of 680 atm over a maximum burning time of about 160 milliseconds.

In the NOL program, the performance of the igniter has been varied (1) by varying the weight of ignition material charged to the igniter, (2) by using ignition-material pellets of different sizes and chemical composition, (3) by varying the throat and exit areas of the igniter nozzle and (4) by varying the volume of the combustion chamber. By a systematic variation of these parameters (different "shot conditions") it is possible to obtain a wide range of igniter output characteristics needed for a fairly complete study of rocket ignition.

Additional information on the igniter design (12,16), the instrumentation designed for use with the igniter (2), and the role of the igniter in the NOL ignition program (17) have, or will be, reported.

The ignition material used in the igniter consists of small cylindrical-pellets. Three different chemical compositions of ignition material have been studied in the NOL program. One composition, M2 propellant, is a double-base material (10). Another composition, specially developed for the NOL ignition work, consists of a double-base material and a metal additive (22). The third composition, a commonly used ignition material, consists of an oxidizer plus a metal additive (13). In this report, these last two compositions will be called "Ignition Materials B and C", respectively.

In Table I, the available (or estimated) chemical, physical, thermodynamic, and ballistic properties of the ignition materials are tabulated. As noted from the table, it is possible to obtain a wide range of solid-to-gas ratios of ignition material combustion products: ranging from 94% in the case of Ignition Material C to almost 0% in the case of the M2 composition.

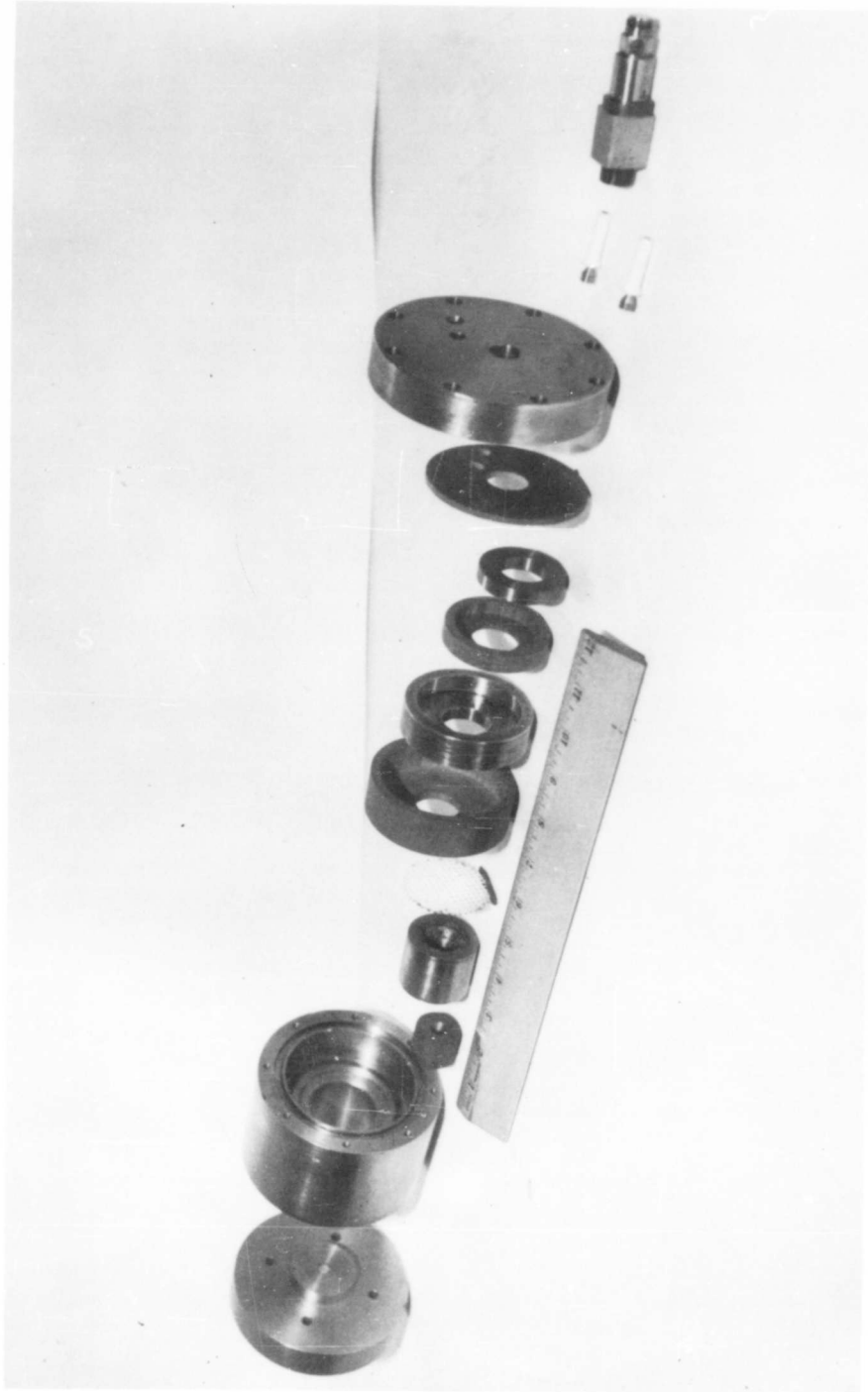


FIG. 1 AN EXPLODED-VIEW PHOTOGRAPH OF THE "HI-LO" IGNITER

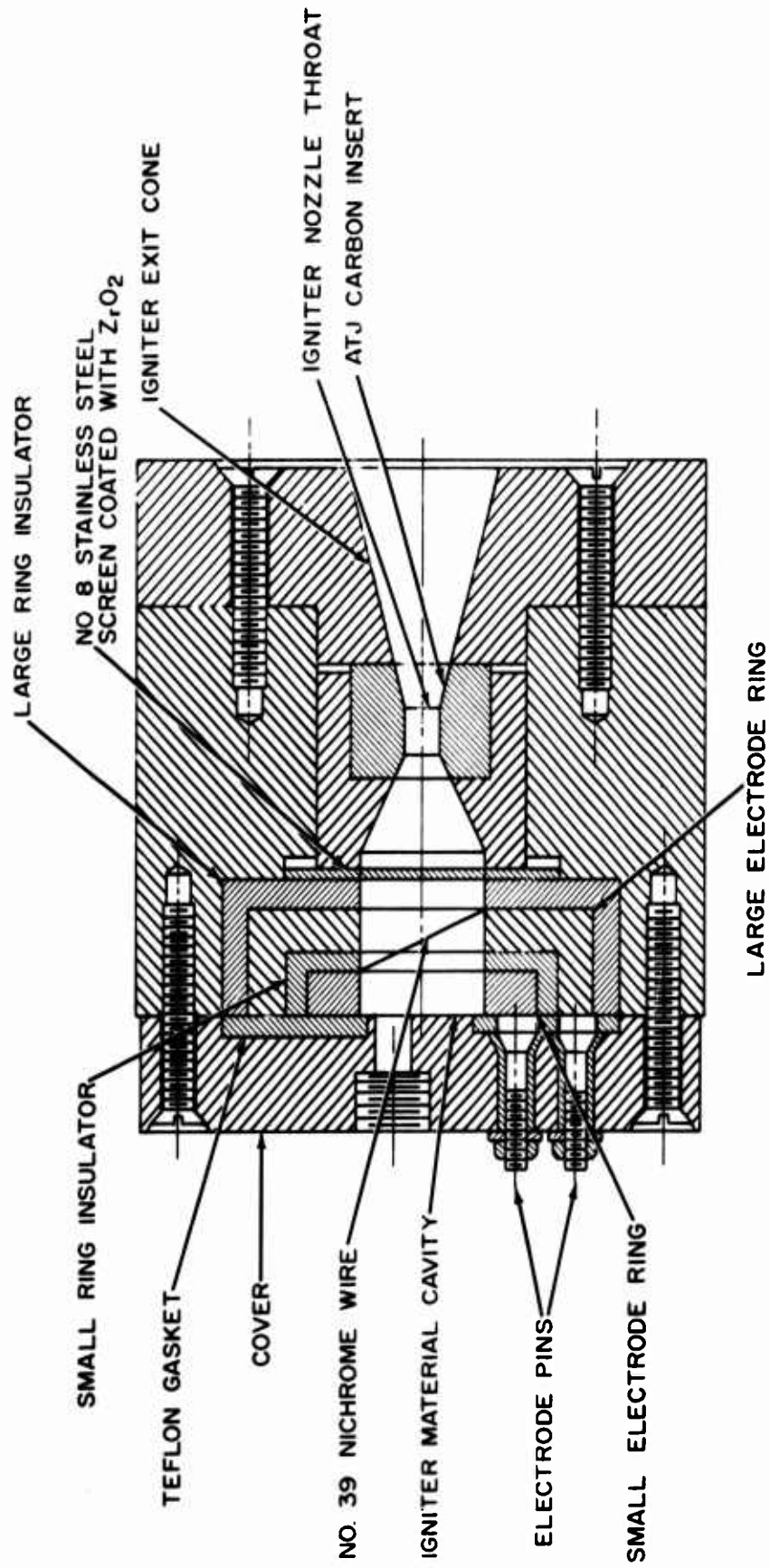


FIG. 2 A SCHEMATIC DRAWING OF THE HI-LO" IGNITER

TABLE I A TABLE OF THE PHYSICAL, CHEMICAL, THERMODYNAMIC AND BALLISTIC PROPERTIES OF THREE IGNITION MATERIALS

IGNITION MATERIAL	CHEMICAL & PHYSICAL CHARACTERISTICS		THERMODYNAMIC PROPERTIES					BALLISTIC PROPERTIES		
	COMPOSITION	DENSITY ρ_p (GM/CM ³)	HEAT OF COMBUSTION h_c (CAL/GM)	FLAME TEMPERATURE T_c (°K)	SPECIFIC HEAT RATIO γ	RATIO OF PROD. GASES TO NON-GASES $\frac{d}{d_0}$ (WT FRACTION)	BURNING RATE $r = ap^n$	IMPETUS I (FT-LBS/LBM)		
							$\left(\frac{\text{IN}}{\text{SEC}} \left(\frac{\text{LB}}{\text{IN}^2}\right)^{-n}\right)$			
M2 ^a	NITROGLYCERINE NITROCELLULOSE	1.65	1080	3319 (ISOCHORIC) 2712 (ISOBARIC)	1.224	0.99	1.03×10^{-3} (AVERAGE 34 TO 550 ATM)	0.88	3.6 X 10 ⁵	
IGNITION MATERIAL B ^b	DOUBLE-BASE MATERIAL + METAL PARTICLES	2.21	1287	~4000 Δ_c (ESTIMATED) (ISOCHORIC) ~3400 Δ_c (ESTIMATED) (ISOBARIC)	~1.18 Δ_c (ESTIMATED)	0.54	7.8×10^{-3} (AVERAGE 34 TO 140 ATM)	0.71	3.4×10^5	Δ_c
IGNITION MATERIAL C ^c	OXIDIZER MATERIAL + METAL PARTICLES	1.67	1500	~2500 Δ_c (ESTIMATED) (ISOCHORIC) ~2100 Δ_c (ESTIMATED) (ISOBARIC)	~1.18 Δ_c (ESTIMATED)	0.06	1.6×10^{-2} (AVERAGE 34 TO 140 ATM)	0.63	1.6×10^5	Δ_c

^a REF 10^b REF 13, 22^c ESTIMATED WITH THE USE OF METHODS SUGGESTED BY ALTMAN (1)^d CALCULATIONS BASED ON ROOM TEMPERATURE CONDITIONS^e EXPERIMENTALLY DETERMINED (BASED ON HIGH-PRESSURE BOMB SHOTS)

Ignition Materials B and C were first used in the experimental work since the latter was a commonly used ignition material and the former appeared to be a promising ignition-material composition. As will be shown, the evaluation of the igniter output and internal ballistics with the use of these materials presented numerous complications because of the non-gaseous phases in the combustion products (see Table 1). Therefore, it was decided to concentrate on the use of an ignition material that produces essentially all gaseous combustion products; that is, the M2 material. (The use of an essentially gaseous igniter output also simplifies the analytical treatment of the igniter-product distribution in the NOL research rocket).

Approximately 400 igniter shots have been made using the three ignition materials. A fast-response pressure probe (a crystal transducer) is used to measure the pressure developed in the igniter. The response of the probe is fed through an electrometer circuit to a recording oscillograph. A digital-computer program (IBM 7090) is used to convert the "raw" data from the probes into pressure-time and integral-pressure-time data.

Reproducibility of the igniter shots, based on at least three repeats of the same shot condition, is satisfactory. For Ignition Materials B and C, fired under a variety of shot conditions, the maximum pressures developed in the igniter for the repeat shots show a standard deviation from the mean of $\pm 5\%$ (see Tables 3 and 4). For M2 pellets, the deviation from the mean is about $\pm 10\%$ (see Table 2). Further refinement of the igniter and pellet design is planned in order to improve the reproducibility of the M2 shots even further.

C. SCHEME FOR EVALUATING IGNITER PERFORMANCE

The objectives of the igniter studies are threefold: (1) to find the best means of predicting the igniter performance; (2) to evaluate the relative importance of each performance characteristic in the ignition of a rocket; and (3) to determine how much control of the performance characteristics is possible with the present design of the "Hi-Lo" igniter.

The performance characteristics of the igniter are grouped into two broad categories: (1) the internal ballistic parameters; and (2) the output parameters. An understanding of the output parameters is of major importance since the output directly affects the ignition of a rocket. Data on the internal-ballistic parameters are of value in determining the output parameters and

TABLE 2. TABULATED SHOT DATA FOR THE IGNITER USING M2 IGNITION MATERIAL

M_0 (gm)	A_t (cm ²)	V_c (cm ³)	K	Δ (gm/cc)	$K\Delta$ (gm/cc)	$(P_0)_{max}$ (atm)	$\int P dt$ (atm-sec)	C_D gm (sec-atm-cm ²)		
6.01	0.317	20.1	384	0.378	145	445	2.90	6.54		
6.02	"	"	385	0.377	"	410	--	--		
6.01	"	"	"	"	"	478	--	--		
6.03	"	"	"	"	"	421	--	--		
6.02	"	"	"	"	"	440	--	--		
5.84	0.317	20.1	374	0.364	136	407	--	--		
5.85	"	"	"	"	"	382	--	--		
5.82	"	"	371	0.367	"	421	2.82	6.51		
5.82	"	"	"	"	"	441	--	--		
5.83	"	"	"	"	"	370	2.69	6.84		
5.83	"	"	"	"	135	460	2.74	6.71		
5.82	"	"	"	"	"	424	--	--		
5.83	"	"	"	0.362	"	369	--	--		
6.02	0.438	20.1	278	0.378	105	337	--	--		
4.54	0.317	"	289	0.270	78	133	--	--		
4.54	"	"	290	"	"	125	--	--		
4.54	"	"	"	0.266	77	127	--	--		
4.52	"	"	289	"	"	146	--	--		
4.52	"	"	"	"	"	132	--	--		
4.51	"	"	288	0.267	"	129	--	--		
4.52	"	"	289	0.266	"	125	--	--		
4.52	"	"	288	0.267	"	120				
4.53	"	"	289	0.266	"	122				
4.53	"	"	"	"	"	118	--	--		
4.52	"	"	"	"	"	111	--	--		
4.53	"	"	290	"	"	111	--	--		
4.53	"	"	289	"	"	132	1.87	7.64		
4.52	"	"	"	"	"	125	1.88	7.58		
4.52	"	"	"	"	"	147	2.00	7.13		
4.53	"	"	"	"	"	119	1.65	8.66		
4.52	"	"	"	"	"	131	1.67	8.54		
4.53	"	"	"	"	"	131	1.72	8.30		
4.54	"	"	"	"	"	148	1.76	8.14		
4.52	"	"	"	"	"	140	1.79	7.97		
4.53	"	"	"	"	"	133	1.65	8.66		
4.52	"	"	"	"	"	124	1.57	9.08		
4.53	"	"	"	"	"	142	1.76	8.12		
4.52	"	"	"	"	"	147	1.80	7.92		
4.52	"	"	"	"	"	140	--	--		
4.52	"	"	"	"	"	127	1.79	7.97		
4.53	"	"	"	"	"	137	1.61	8.88		
4.51	"	"	"	"	"	135	1.63	8.73		
4.51	"	"	288	0.264	76	139	--	--		
3.03	0.317	10.3	193	0.368	71	97	--	--		
4.53	0.438	20.1	209	0.268	56	87	1.20	8.61		
3.65	0.317	"	233	0.206	48	48	--	--		
3.03	"	"	193	0.171	33	33	2.52	3.79		
3.06	"	"	195	0.169	33	37	2.68	3.60		



TABLE 3. TABULATED SHOT DATA FOR THE IGNITER USING IGNITION MATERIAL B

M ₀ gm	A _t (cm ²)	V _c (cm ³)	K	Δ (gm/cc)	K Δ (gm/cc)	C _{max} (atm)	∫ P dt (atm-sec)	C _D gm (atm-sec-cm ²)
5.80	.045	20.1	660	.335	221	544	14.3	9.1
5.77	.045	20.1	617	.332	205	522	12.7	10.2
5.85	.079	20.1	608	.336	204	607	7.3	10.2
5.83	.193	10.4	253	.777	197	414	3.7	8.3
9.56	.317	17.4	252	.735	185	479	3.8	7.9
9.56	.317	20.1	275	.625	172	507	3.4	8.9
9.53	.317	20.1	264	.614	162	420	3.6	8.4
9.51	.522	13.7	152	1.057	161	494	1.8	10.0
9.52	.178	20.1	252	.606	153	320	6.2	8.6
5.85	.124	20.1	398	.336	134	440	5.6	8.4
5.87	.124	20.0	398	.337	134	449	5.4	8.8
5.87	.317	10.3	167	.794	133	312	--	--
5.89	.317	10.3	167	.796	133	324	2.3	8.1
5.80	.124	20.1	395	.333	132	435	5.1	9.2
5.79	.124	20.1	395	.333	132	414	5.3	8.8
5.87	.126	20.1	387	.337	130	447	5.3	8.7
5.86	.317	10.3	165	.781	129	282	--	--
5.88	.079	20.1	347	.338	117	376	8.2	8.7
5.82	.079	20.1	347	.334	116	344	8.0	9.2
5.82	.079	20.1	347	.334	116	327	8.2	9.0
5.80	.079	20.1	347	.333	116	371	8.6	8.5
5.83	.079	20.1	347	.335	116	333	8.1	8.7
5.81	.079	20.1	347	.334	116	362	8.0	9.2
5.81	.079	20.1	347	.334	116	382	8.1	9.1
3.63	.124	10.3	245	.422	103	212	3.2	9.1
5.83	.193	20.1	256	.339	102	225	--	--
9.51	.503	20.1	163	.607	99	329	3.0	6.3
5.81	.193	17.4	249	.395	98	224	3.4	8.9
9.52	.294	20.1	153	.606	93	204	3.8	8.5
5.85	.177	20.1	275	.336	92	270	3.9	8.5
5.85	.177	20.1	275	.336	92	323	3.7	8.9
5.84	.177	20.1	273	.336	92	311	3.7	8.9
5.83	.177	20.1	273	.335	91	309	3.9	8.4
5.80	.177	20.1	273	.333	91	325	3.6	9.1
5.85	.105	20.1	260	.336	87	211	6.4	8.7
5.86	.503	10.4	97	.761	74	146	1.8	6.5
9.85	.493	20.1	102	.652	67	109	3.3	5.9

5.83	.193	20.1	256	.339	102	225	--	--
9.51	.503	20.1	163	.607	99	329	3.0	6.3
5.81	.193	17.4	249	.395	98	224	3.4	8.9
9.52	.294	20.1	153	.606	93	204	3.8	8.5
5.85	.177	20.1	275	.336	92	270	3.9	8.5
5.85	.177	20.1	275	.336	92	323	3.7	8.9
5.84	.177	20.1	273	.336	92	311	3.7	8.9
5.83	.177	20.1	273	.335	91	309	3.9	8.4
5.80	.177	20.1	273	.333	91	325	3.6	9.1
5.85	.105	20.1	260	.336	87	211	6.4	8.7
5.86	.503	10.4	97	.761	74	146	1.8	6.5
9.85	.493	20.1	102	.652	67	109	3.3	5.9
3.60	.193	10.4	156	.419	65	149	2.1	8.9
3.63	.068	17.0	256	.237	61	138	5.6	9.4
3.67	.124	17.4	250	.234	59	147	2.7	11.0
5.85	.317	20.1	169	.342	58	143	2.0	9.2
5.85	.317	20.1	167	.340	57	140	1.5	12.3
5.87	.317	20.1	167	.341	57	147	--	--
5.97	.317	20.1	167	.341	57	184		
3.62	.124	20.1	267	.208	56	148	2.5	11.7
5.87	.317	20.1	165	.340	56	136	--	--
5.89	.317	20.1	165	.340	56	176		
5.87	.317	20.1	165	.339	56	147	--	--
5.87	.317	20.1	165	.339	56	138	1.9	9.7
5.83	.317	20.1	165	.337	56	127	2.1	8.8
5.81	.317	20.1	165	.336	55	140	1.8	10.2
5.81	.178	20.1	165	.336	55	107	3.6	9.1
5.81	.178	20.1	165	.336	55	129	3.9	8.4
5.83	.317	20.1	161	.337	54	142	1.9	9.7
5.70	.178	20.1	164	.329	54	93	2.7	11.9
5.87	.317	20.1	157	.334	53	133	--	--
5.87	.317	20.1	154	.337	52	112	--	--
5.85	.317	20.1	154	.336	52	117	--	--
5.81	.317	20.1	157	.334	52	109	--	--
5.81	.317	20.1	154	.334	52	152	2.0	9.2
5.88	.317	20.1	154	.337	52	127	--	--
5.88	.317	20.1	154	.338	52	117	2.0	9.3
5.85	.317	20.1	154	.336	52	142	2.0	9.2
5.88	.317	20.1	154	.338	52	142	2.2	9.4
5.85	.317	20.1	154	.336	52	142	1.7	10.9
5.84	.178	20.1	154	.336	52	110	3.1	10.6
5.86	.178	20.1	154	.337	52	116	3.6	9.4

5.81	.178	20.1	165	.336	55	107	3.6	9.1	
5.81	.178	20.1	165	.336	55	129	3.9	8.4	
5.83	.317	20.1	161	.337	54	142	1.9	9.7	
5.70	.178	20.1	164	.329	54	93	2.7	11.9	
5.87	.317	20.1	157	.334	53	133	--	--	
5.87	.317	20.1	154	.337	52	112	--	--	
5.85	.317	20.1	154	.336	52	117	--	--	
5.81	.317	20.1	157	.334	52	109	--	--	
5.81	.317	20.1	154	.334	52	152	2.0	9.2	
5.88	.317	20.1	154	.337	52	127	--	--	
5.88	.317	20.1	154	.338	52	117	2.0	9.3	
5.85	.317	20.1	154	.336	52	142	2.0	9.2	
5.88	.317	20.1	154	.338	52	142	2.2	9.4	
5.85	.317	20.1	154	.336	52	142	1.7	10.9	
5.84	.178	20.1	154	.336	52	110	3.1	10.6	
5.86	.178	20.1	154	.337	52	116	3.6	9.4	
5.86	.178	20.1	154	.337	52	111	2.8	11.8	
5.87	.178	20.1	154	.337	52	122	3.4	9.7	
5.80	.317	20.1	152	.333	51	99	--	--	
5.82	.317	20.1	152	.334	51	100	--	--	
5.82	.317	20.1	152	.334	51	139	2.0	9.2	
5.81	.317	20.1	152	.334	51	132	1.9	9.7	
5.81	.317	20.1	152	.334	51	152	2.0	9.3	
5.82	.178	20.1	154	.334	51	99	3.3	9.9	
5.82	.178	20.1	154	.334	51	105	3.2	10.2	
5.82	.178	20.1	154	.334	51	103	3.2	10.2	
5.86	.178	20.1	151	.337	51	84	3.3	10.0	
3.62	.068	20.1	256	.198	51	166	5.8	9.2	
5.83	.178	10.4	146	.335	49	136	--	--	
3.29	.177	20.1	154	.296	46	88	1.9	9.8	
3.61	.317	10.4	97	.415	40	76	1.2	9.5	
5.85	.506	20.1	103	.340	35	82	1.1	10.5	
5.84	.506	20.1	103	.340	35	81	1.2	9.6	
3.61	.106	20.1	170	.187	32	70	3.0	11.3	
5.87	.294	20.1	91	.334	31	50	--	--	
3.64	.193	20.1	156	.198	31	67	1.7	11.1	
3.65	.193	20.1	156	.199	31	72	--	--	
3.30	.177	20.1	154	.177	27	61	1.5	12.4	
3.25	.177	20.1	154	.175	27	62	1.3	14.1	
3.29	.177	20.1	154	.177	27	66	1.6	11.6	
3.62	.317	20.1	95	.197	19	31	.8	14.2	
3.99	.317	20.1	78	.213	17	93	.8	15.7	

TABLE 4. TABULATED SHOT DATA FOR THE IGNITER USING IGNITION MATERIAL C

M ₀ (gm)	A _f (cm ²)	V _c (cm ³)	K	Δ (gm/cc)	KΔ (gm/cc)	P ₂ C _{max} (atm)	∫ Pdt (atm-sec)	C _D gm (atm-sec-cm ²)	
9.59	.0794	20.1	1123	.652	732	281	7.6	15.9	
9.51	.0794	20.1	1123	.647	727	356	10.7	11.2	
9.55	.0794	20.1	1114	.650	724	318	8.2	14.7	
9.52	.0794	20.1	1114	.647	721	333	8.7	13.8	
5.86	.0794	10.3	707	.837	592	273	5.7	13.0	
5.18	.0197	20.1	1754	.305	535	205	13.7	19.1	
4.46	.0197	20.1	2074	.253	525	245	15.2	14.9	
4.42	.0197	20.1	2074	.251	521	198	13.2	17.0	
4.41	.0197	20.1	2074	.251	521	190	12.7	17.6	
4.40	.0197	20.1	2074	.250	519	229	11.8	18.9	
4.40	.0197	20.1	2074	.250	519	243	16.3	13.7	
4.40	.0197	20.1	2074	.250	519	227	15.0	14.9	
5.86	.0484	20.1	1119	.349	390	243	7.8	15.5	
8.85	.178	20.1	460	.586	270	149	--	--	
4.13	.0794	10.3	482	.516	249	168	3.9	13.3	
5.88	.0794	20.1	682	.361	246	167	--	--	
5.86	.0794	20.1	682	.350	239	172	--	--	
5.86	.0794	20.1	682	.350	239	156	4.8	15.4	
5.84	.0794	20.1	682	.348	237	140	--	--	
5.83	.0794	20.1	682	.347	237	138	5.2	14.1	
5.84	.128	20.1	423	.348	147	117	2.8	16.3	
6.64	.178	20.1	345	.405	140	94	--	--	
5.22	.0794	20.1	436	.307	134	105	4.4	14.7	
5.20	.0794	20.1	436	.306	133	103	4.4	14.9	
5.17	.0794	20.1	436	.304	133	110	4.5	14.5	
5.14	.0794	20.1	436	.302	132	110	4.6	14.1	
5.15	.0794	20.1	436	.303	132	103	4.9	13.2	
4.41	.0794	20.1	516	.251	130	125	3.6	15.4	
4.43	.0794	20.1	516	.252	130	110	3.9	14.3	
4.14	.0794	20.1	482	.233	112	99	3.0	17.4	
5.87	.178	20.1	301	.347	104	82	--	--	
5.77	.178	20.1	300	.341	102	86	2.9	11.2	
3.42	.0794	20.1	350	.188	66	71	2.7	16.0	
3.40	.0794	20.1	350	.188	66	70	2.6	16.5	
5.96	.317	20.1	175	.357	62	48	--	--	
5.90	.317	20.1	173	.353	61	48	--	--	
5.92	.317	20.1	173	.354	61	56	--	--	
5.91	.317	20.1	173	.354	61	48	--	--	
5.93	.317	20.1	171	.353	60	48	--	--	
5.15	.178	20.1	194	.303	59	54	--	--	
5.15	.178	20.1	194	.303	59	48	--	--	
4.52	.178	20.1	230	.257	59	50	--	--	
4.42	.178	20.1	230	.251	58	64	2.0	12.4	
4.41	.178	20.1	230	.251	58	60	1.8	13.8	
4.41	.178	20.1	230	.251	58	60	1.8	13.8	
4.43	.178	20.1	230	.252	58	55	2.9	11.2	
4.43	.178	20.1	230	.252	58	50	--	--	
4.43	.317	20.1	129	.252	33	34	--	--	
4.41	.317	20.1	129	.251	32	29	--	--	

in providing information for modifying or scaling-up the igniter.

The procedures used to evaluate the performance of the igniter are summarized in Fig. 3. The evaluation techniques will be presented according to the following outline:

Determination of Igniter Internal Ballistics

The first section of this report will discuss in order, the following methods that have been used to characterize the igniter internal ballistics:

1. Theoretical Prediction of Igniter Pressurization - based on a model used to describe the burning of the igniter pellets in terms of the igniter geometry and the physical, thermodynamic and ballistic properties of the ignition material.
2. Experimental Determination of Ignition-Material Ballistic and Thermodynamic Properties - based on experiments performed in a closed-bomb and a non-vent vessel (a rocket casing with "plugged" nozzle into which the igniter is vented).
3. Empirical Correlation of Measured Igniter Pressure Data - based on empirical equations which relate the maximum pressure developed in the igniter to the igniter shot conditions.

Output Parameters

The second section of this report will discuss the methods that have been used to characterize the igniter output. These methods make use of the internal-ballistic studies and studies made of the igniter output as it is discharged into vented and non-vented vessels.

Based on a study made of the physical-chemical, hydrodynamic and engineering factors involved in rocket ignition (17), the characterization of the igniter output has been divided into a study of four parameters:

1. The MASS Output
 - a. Quantity of Mass - based on a study of the deposition and accumulation of igniter products inside

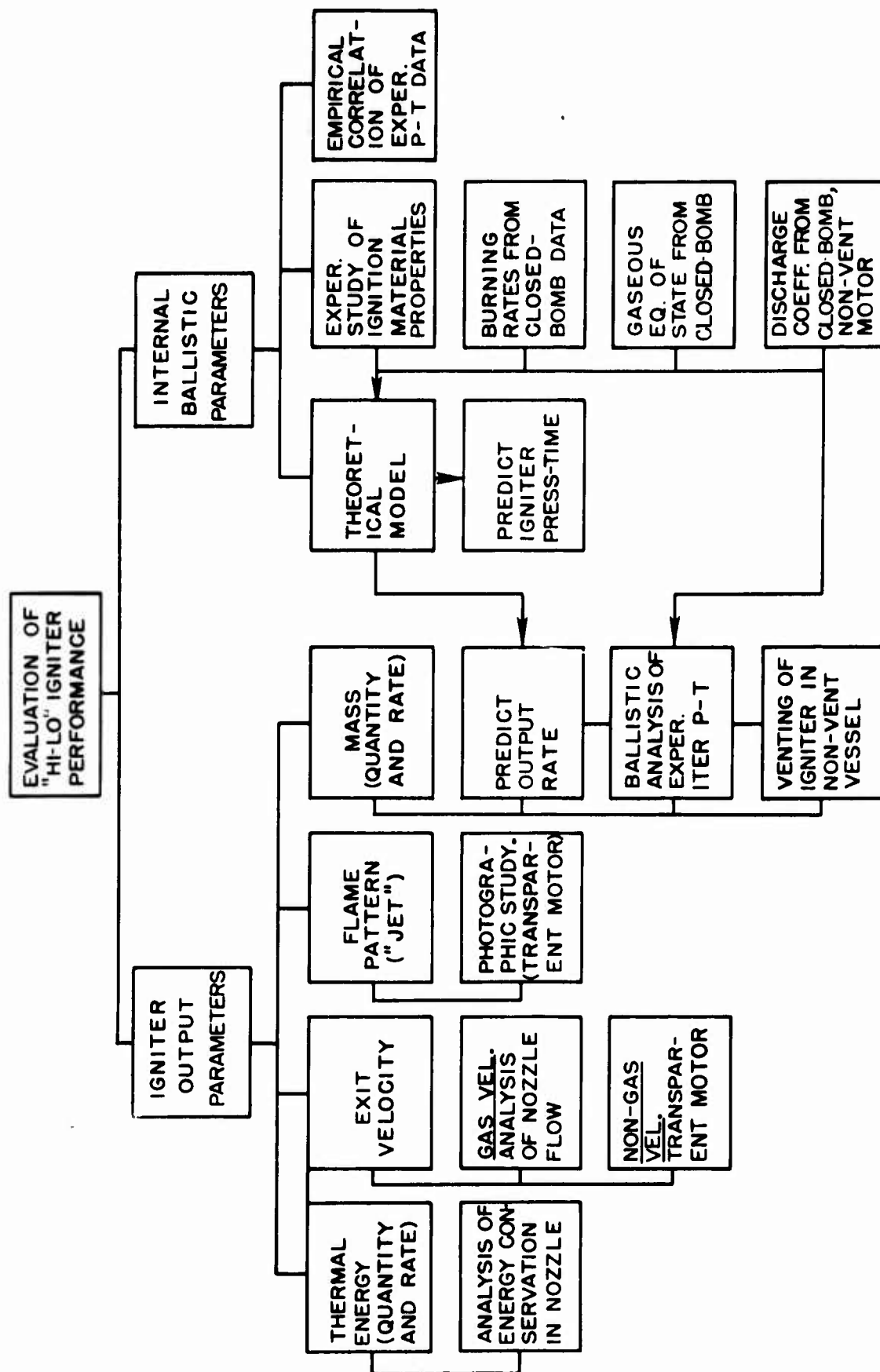


FIG. 3 A BLOCK DIAGRAM OUTLINE OF THE IGNITER - EVALUATION SCHEME

the igniter.

- b. Mass Venting Rate - based on (1) the predicted (theoretical model) or measured pressurization of the igniter and suitable ballistic relationships and (2) the pressurization rate of a non-vent vessel into which the igniter is vented.

2. The THERMAL ENERGY Output

- a. Quantity of Thermal Energy - based on an analysis of the expansion of igniter products in the igniter nozzle.
- b. Thermal-Energy Venting Rate - based on nozzle-flow studies and mass output-rate data.

3. The EXIT VELOCITY of the Igniter Products

- a. Gaseous Output - based on isentropic-flow relationships
- b. Non-Gaseous Output - based on a photographic study of the output as it is vented into a transparent motor casing.

4. The FLAME PATTERN Assumed by the Output Products - based on a photographic study of the igniter output flame.

II. DETERMINATION OF IGNITER INTERNAL BALLISTICS

Relationships that can be used to predict the pressurization of the "Hi-Lo" igniter by the ignition combustion products are of value for two reasons: (1) the pressure-time data can be used to determine what is vented from the igniter; that is, the output characteristics, and (2) information on the internal ballistics of this type of igniter can be used to design modified or scaled-up versions of the igniter with a minimum of trial and error experimentation. This section will describe two methods that have been used at NOL to predict the pressurization of the igniter. One method is based on a theoretical description of the production and venting of the igniter combustion products and results in a predicted pressure-time curve. For use in this theoretical study (and other ballistic analyses), experiments were run to determine the ballistic and thermodynamic properties of the ignition materials. The second method predicts maximum igniter pressures by means of an empirical

correlation of various igniter parameters.

A. THEORETICAL PREDICTION OF IGNITER PRESSURIZATION

A theoretical model was constructed (23) to describe the igniter pressurization in terms of the physical, thermodynamic and ballistic properties of the igniter pellets and the geometry of the igniter. The object was to develop equations expressing pressure as a function of time for the combustion of a number of solid cylindrical pellets. The first model constructed was based on the usual assumptions used in ballistic work - that is:

- (1) The combustion products obey the perfect gas law.
- (2) No frictional or heat losses occur in the igniter chamber or nozzle.
- (3) The ignition material is ignited simultaneously on all surfaces.
- (4) The pellets burn according to the steady-state, linear burning-rate equation determined for the material; i.e., no deviations from the burning-rate equation occur as a result of rapid pressure changes in the igniter.

The burning-rate equation of the pellets is

$$dX/dt = r = a P_C^n \quad (1)$$

where X is the distance burned into the pellet at any time

t is time

r is the linear burning rate of the ignition material

a is the burning-rate constant

n is the burning-rate exponent

P_C is the igniter pressure

From geometric considerations

$$S = N\pi(D_0 - 2X)(L_0 + 1/2D_0 - 3X) \quad (2)$$

where S is the total burning surface of the pellets

N is the number of pellets loaded in the igniter

L_0 is the initial pellet length

D_0 is the initial pellet diameter

and

$$V_F = V_C - N\pi/4(D_0 - 2X)^2(L_0 - 2X) \quad (3)$$

where V_F is the igniter free volume (the chamber volume minus the total volume of pellets)

V_C is the igniter chamber volume

Writing a mass balance in the igniter:

MASS ACCUMULATED IN THE IGNITER = MASS PRODUCED - MASS VENTED

By substitution of suitable ballistic equations for each of the terms in the mass balance, the following equation resulted:

$$dP_C/dt = [I(aP_C^n \rho_P S - C_D A_t P_C) - (P_C S a P_C^n)] / V_F \quad (4)$$

where ρ_P is the density of the pellets

I is the impetus of the ignition material (flame temperature x ideal gas constant/combustion-product molecular weight)

C_D is the nozzle discharge coefficient

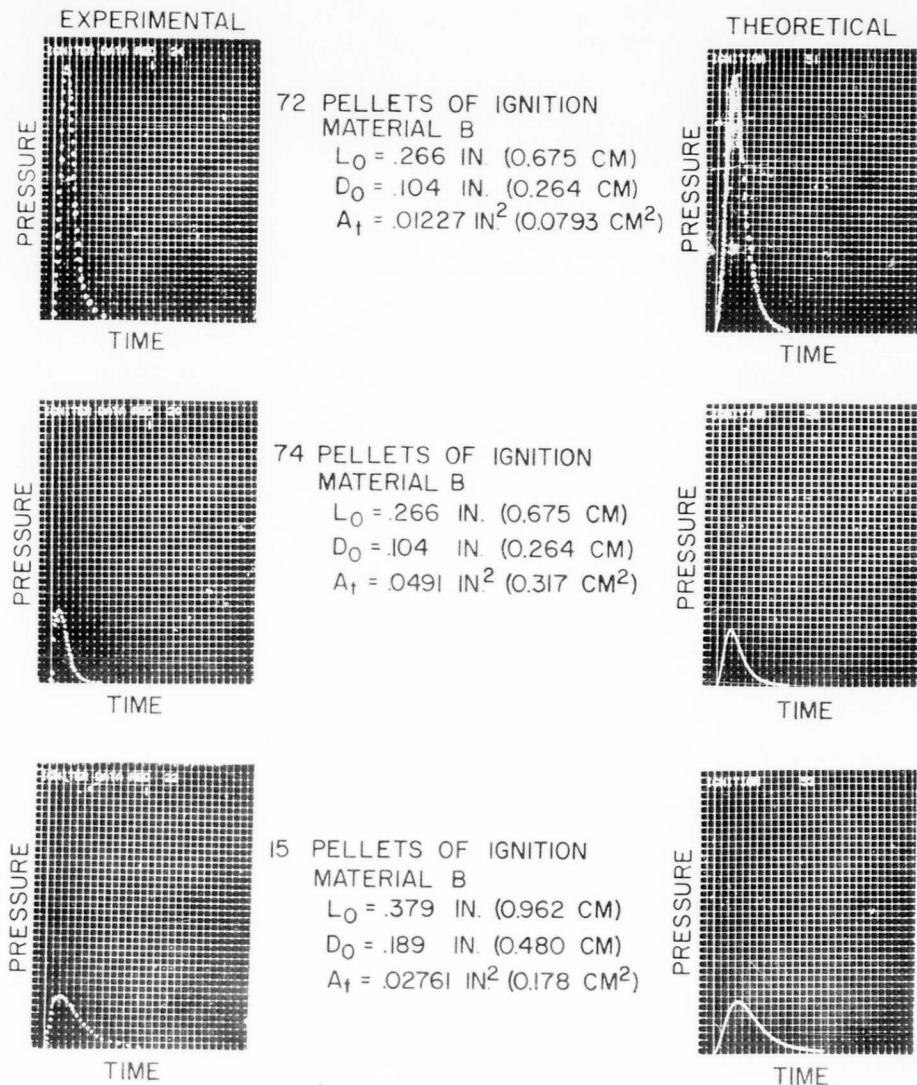
A_t is the nozzle throat area

Equations 1 through 4 were converted into finite difference equations and coded for solution on the IBM digital computer.

Check of Theoretical Model

A number of igniter shots were performed in an attempt to duplicate the data obtained with the use of the theoretical igniter model. Pellets of Ignition Material B were used in this check. The pressure developed in the igniter was measured for shots in which the following ignition material and igniter parameters were systematically varied: the weight of ignition material used in the shot, M_0 ; the chamber volume of the igniter, V_C ; the size of the cylindrical igniter pellets, $-L$ (length), D^C (diameter) and L/D (ratio); and the throat area of the igniter nozzle, A_t . The maximum pressures obtained for the shot series are summarized in Table 3. Most of the listed pressures represent an average of two or more shots.

Comparison of the experimental and theoretical shot data indicated that, with the exception of a few shot conditions, such as those presented in Fig. 4, significant disagreement



THIS FIGURE SHOWS CORRESPONDING EXPERIMENTAL AND THEORETICAL PRESSURE TIME CURVES FOR THREE DIFFERENT IGNITER FIRINGS. THE VERTICAL AND HORIZONTAL GRID LINES REPRESENT 17 ATMS AND 5 MILLISECONDS, RESPECTIVELY.

FIG. 4 THEORETICAL AND EXPERIMENTAL PRESSURE-TIME CURVES FOR THE "HI-LO" IGNITER

occurred between predicted and measured pressure data. The theoretical pressures of Fig. 5 were computed with the use of an "adjusted" impetus value to give the best agreement between the experimental and theoretical results. To explain the discrepancies, the assumptions used in the construction of the theoretical model were carefully evaluated. It was believed that the deviations in the pressure data could be attributed mainly to three factors. First, the theoretical burning-rate laws for the pellets may not hold when the pressure is varying rapidly. Some evidence does exist which links burning-rate deviations with pressure transients (21). Second, the combustion products from the ignition material will deviate from the ideal gas law when the products contains significant amounts of non-gaseous materials. Third, deviation from the theoretical value of the discharge coefficient might occur as a result of heat losses to the igniter parts, non-equilibrium combustion and nozzle inefficiency. Fourth, the impetus of the ignition material is also affected by any heat losses.

The fundamental studies undertaken to quantitatively evaluate the first three of these factors are discussed in the following section.

B. EXPERIMENTAL STUDIES OF IGNITION MATERIAL BALLISTIC AND THERMODYNAMIC PROPERTIES

Experimental studies were undertaken to determine the ballistic (discharge coefficient and burning rate) and thermodynamic (equation-of-state) properties of the ignition materials. The results of these studies were used in the theoretical study described above and in the ballistic-output analysis discussed in Section III A2.

1. Discharge Coefficient. Ideally, the nozzle discharge coefficient, C_D , of a propellant or pyrotechnic material depends only on the thermodynamic properties of the combustion products: primarily, the combustion temperature and molecular weight of the products and secondarily, the product specific heat ratio. Studies were made to determine the extent and the nature of the deviations from the theoretical C_D that may take place in the igniter. Two types of deviations are of interest: (1) deviations in C_D at different igniter-shot conditions and (2) deviations in C_D during a shot.

a. Variation of C_D With the Shot Condition

The determination of C_D for the three ignition materials was made with the use of a standard ballistic equation:

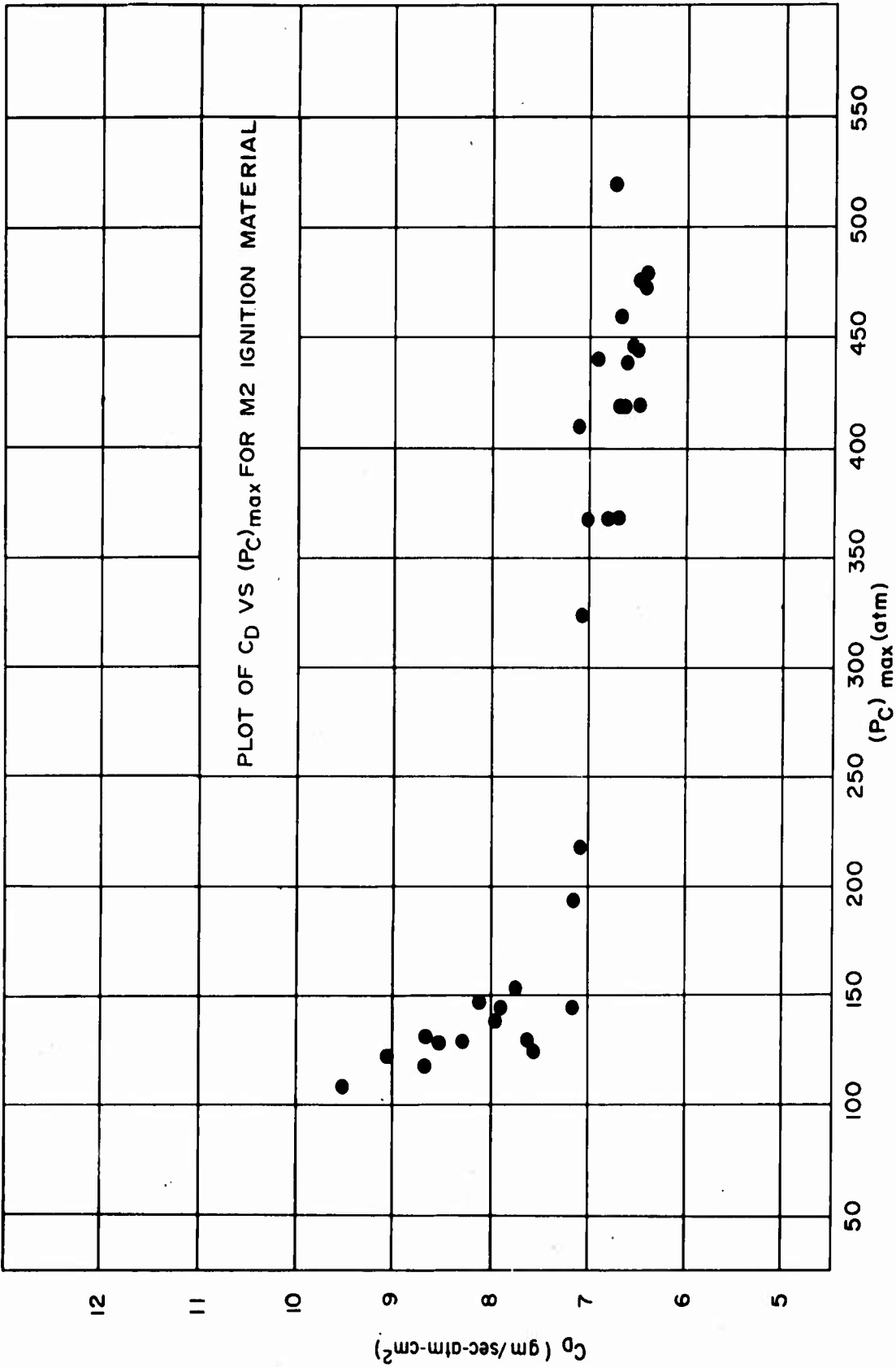


FIG. 5 A PLOT OF NOZZLE DISCHARGE COEFFICIENT VS IGNITER MAXIMUM PRESSURE FOR M2 IGNITION MATERIAL

$$C_D = M_o / A_t (\int P dt)_{total} \quad (5)$$

where M_o is the weight of ignition material used in the shot

A_t is the nozzle throat area

$(\int P dt)_{total}$ is the value of the pressure-time integral (area under the pressure-time curve)

The major assumptions involved in the use of Eq. 5 are: (1) no heat losses in the igniter, (2) no friction losses in the nozzle and (3) ideal gas behavior of the combustion products.

It is believed that the main reason for deviations in C_D is the loss of heat to the igniter parts. To explore the effects of these heat losses, an attempt was made to correlate C_D values determined with the use of Eq. (5) to igniter shot parameters that might control the heat-transfer process. Two such parameters should be the gas density (inversely proportional to pressure) in the igniter and the time duration of the shot. The results of correlations involving the pressure are given in Figures 5 and 6 in which C_D is plotted against the maximum pressure, $(P_G)_{max}$, developed in a variety of igniter shots using pellets of M2 and Ignition Material B (see Tables 2 and 3).

Most of the M2 data came from tests in which the igniter was discharged into a non-vent vessel. Since the igniter was vented into a closed chamber, the final igniter pressure was greater than atmospheric. Consequently, a small correction was necessary to allow for gas accumulation in the igniter chamber at the final pressure. This was done by subtracting from M_o the quantity of gas accumulated - as calculated from the perfect gas law.

For both M2 and Ignition Material B, C_D is effectively constant above 150 atms. Below this pressure the C_D values increase sharply: at lower pressures the relative effect of the heat losses becomes greater as a result of the decreased ratio of product density to heat-transfer surface in the igniter. Mean values of C_D for these materials over a range of maximum pressures from 150 to 400 atm. are:

M2 ... 6.71 gm/sec-atm-cm²

Ignition Material B ... 8.78 " "

This range of maximum pressures will be used in the ignition of the NOL test rocket.

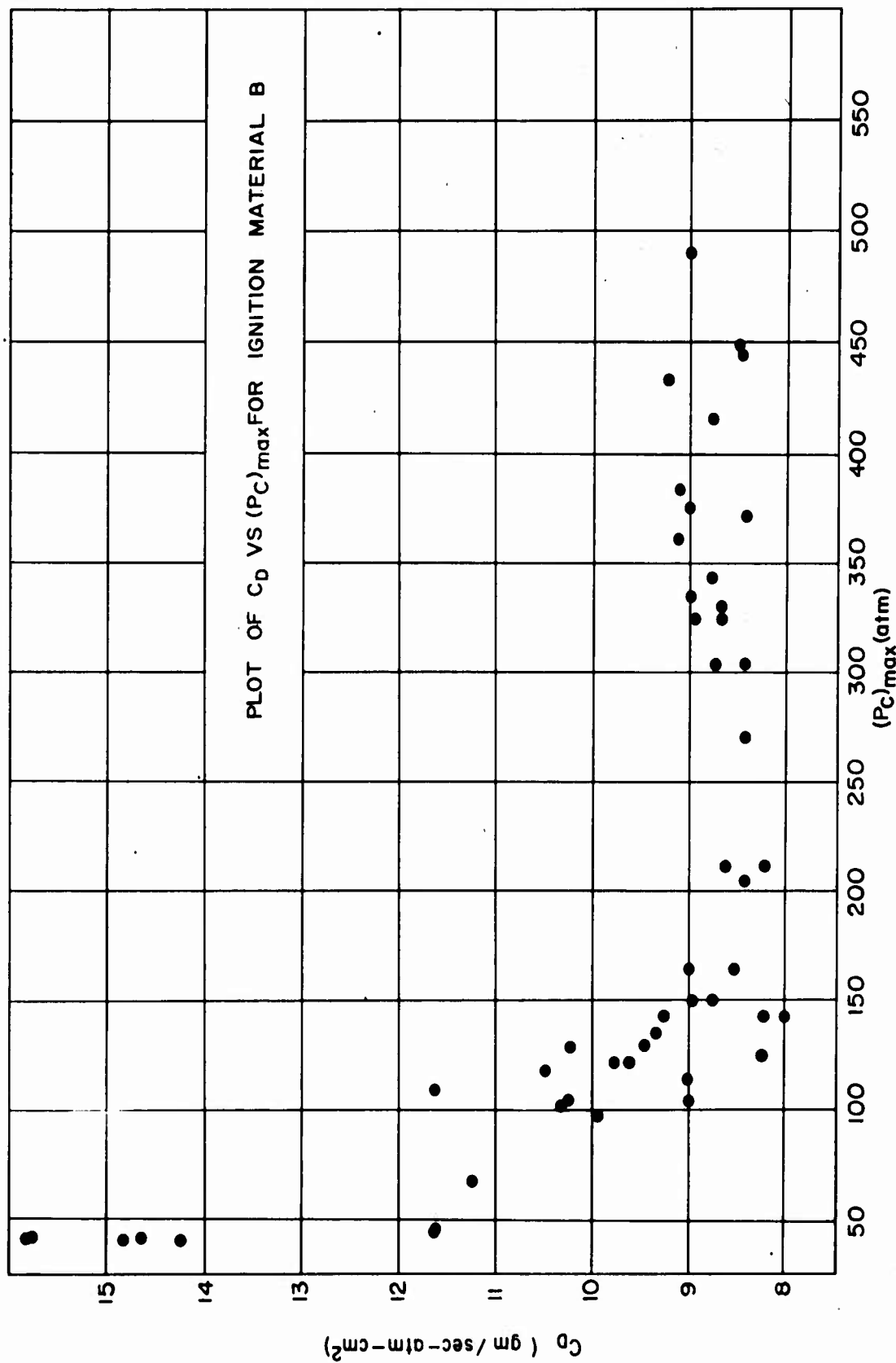


FIG. 6 A PLOT OF NOZZLE DISCHARGE COEFFICIENT VS IGNITER MAXIMUM PRESSURE FOR IGNITION MATERIAL B

In the case of M2 material, a comparison of the experimental C_D was made to the theoretical value calculated from the isobaric flame temperature, the specific heat ratio and the molecular weight reported for the M2 combustion products (10). The calculated value of 6.42 gm/sec-atm-cm² compares quite favorably with the experimental value.

b. Variation of C_D During a Shot

Studies have been started to determine the deviation in C_D during a shot. For this analysis, the experimental data from the non-vent vessel shots described in Section III A2b are used. The pressure probe in the igniter is synchronized with a probe placed a short distance downstream from the igniter in the vessel. It is assumed that the probe in the vessel instantaneously "senses" any change in the igniter pressure. (Because of the very small volume of the igniter combustion chamber and nozzle, a change in the igniter pressure is almost simultaneously reflected in a change in the igniter output to the vessel.)

The C_D analysis consists of three steps. First, the mass output rate over small time intervals is determined from the pressure-and temperature-time data for the igniter output in the vessel with the use of the ideal gas law. Next, a value of the pressure-time integral of the igniter corresponding to any output interval is determined by superimposing the pressure-time trace measured in the vessel on that measured in the igniter. Lastly, the values of the pressure-time integral and mass output for each time interval are substituted in the following incremental form of Eq.(5) to obtain C_D values during the shot:

$$C_D(t) = \Delta m / A_t \int_t^{t+\tau} P dt \quad (6)$$

where Δm is an increment of mass output from the igniter added to the non-vent vessel

τ is the time interval

This analysis is performed on the igniter pressure-time trace from the beginning to the end of the venting process. The venting times, as determined from the vessel pressure (time from zero pressure to maximum vessel pressure), appear to correspond to zero pressure-to-zero pressure times in the igniter for the igniter shots studied so far.

2. Gaseous Equation of State. Ignition material combustion products containing large amounts of non-gaseous materials will not behave as ideal gases. Furthermore, at the high pressures developed in the igniter, deviations from the perfect gas law may occur. Therefore, a study was undertaken to determine with what degree of approximation the ideal gas law could be applied to the use of Ignition Materials B and C in the igniter.

A closed-bomb apparatus was used in this study. The bomb was adapted from one used in a previous NOL ignition study (for design details see Ref. 13). Various-size metal plugs were made to vary the bomb chamber volume, V_C . Shots were made in which the packing density (ratio of ignition pellet weight, M_o , to bomb chamber volume) was varied by using different combinations of M_o , V_C and pellet sizes. A quartz pressure transducer was used to monitor the bomb pressure.

The evaluation of the ideality of the combustion products was made by analyzing the maximum pressures developed in the bomb according to various "standard" equations of state. The object was to determine which equation best "fit" the experimental pressure data.

To demonstrate the use of this method of analysis, the bomb data obtained for a large number of shots using Ignition Material B were analyzed. Shot conditions were varied to give maximum bomb pressures ranging from 25 to 670 atm. The following equations of state were used in the evaluation of the experimental data:

$$P = I_I \Delta \quad \text{Ideal (neglecting volume of ignition material)} \quad (7)$$

$$P = I_C \Delta / 1 - \eta \Delta \quad \text{Co-Volume} \quad (8)$$

$$P = I_E \Delta^C \quad \text{Exponential} \quad (9)$$

$$P = I_V \Delta + E \Delta^2 + F \Delta^3 \quad \text{Virial} \quad (10)$$

where P is the bomb pressure

Δ is the packing density

η is the co-volume value for the Ignition Material B
(29.8 in³/lbm)

I is an "impetus" of the ignition material

E and F are constant coefficients ($2.01 \times 10^9 \text{ lbf-in}^4/\text{lbm}^2$ and $-5.68 \times 10^{11} \text{ lbf-in}^7/\text{lbm}^3$, respectively, for Ignition Material B)

c is a constant coefficient (1.295 for Ignition Material B)

The impetus values determined from the experimental data will be different for each of these equations of state. For purposes of analysis, Equations 7 through 10 were put in the following general form:

$$P/\Delta = f(I, \Delta) \quad (11)$$

The bomb data was then analyzed in terms of each of these P/Δ equations. (The IBM digital computer was used for this analysis.) The results are presented in Fig. 7 along with the experimental data points. From this figure it is clear that the Virial and not the ideal equation of state is the best fit of the bomb data used.

However, because of heat losses that occur in the bomb, more study was needed to confirm the above results. These heat losses are most significant for the low-pressure shots. One way to correct for the losses is to use a method suggested by Sternberg (18). In this method, the heat losses at any time are assumed to be directly proportional to the rate of pressure change occurring in the bomb. The proportionality constant for this relationship can be derived from the "tail-off" portion of the pressure trace; i.e., the drop-off in pressure after the maximum pressure is reached. (The maximum pressure corresponds to the "burn-out" of the igniter pellets.) Preliminary work has been done to program this heat-correction technique for solution on the IBM computer.

3. Burning Rates. A study was made to determine the burning-rate characteristics of ignition materials used in the ignition work. The primary object of the study was to determine whether deviations from the standard, linear burning-rate law occur as a result of the rapid pressure changes that take place in the igniter. A secondary goal was to determine burning rates at pressures not reported in the literature.

The closed-bomb apparatus discussed in the previous section was used for the study. The bomb was operated at high maximum pressures ($>400 \text{ atm}$) to effectively eliminate heat losses to the bomb walls during most of the shot. An analytical program (coded for the IBM computer) has been constructed to compute burning rates (r) as a function of pressure (P) and pressure rate (dP/dt) from the bomb pressure-time data, the geometry of

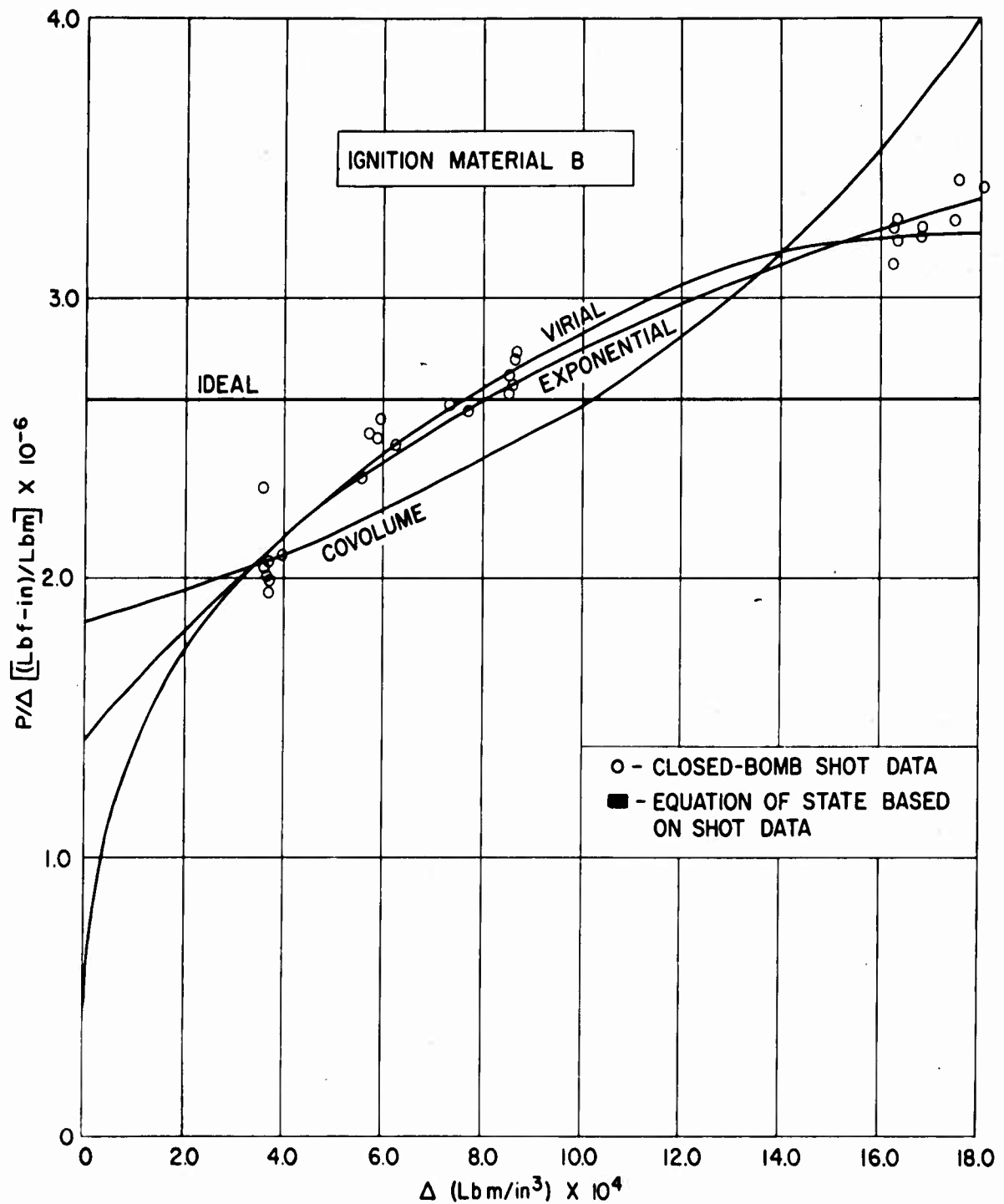


FIG. 7 AN ANALYSIS OF THE GASEOUS EQUATION OF STATE FOR IGNITION MATERIAL B USING CLOSED-BOMB EXPERIMENTS

the igniter pellets and the equation of state for the pellet combustion products. Starting at zero pressure, the build-up of pressure in the bomb over small time intervals (dt) is related to the amount of ignition material that must be burned to produce the pressure change. (For M2 material, the ideal gas law is used in these calculations: for Ignition Materials B and C, equations of state derived in the preceding section will be used). From the geometric relationships for the pellet shape, the mass of ignition material consumed over the time interval is related to the distance burned (dx) into the pellet. In this calculation, it is assumed that the pellets are burning uniformly over the entire pellet surface. These analyses are performed on the bomb pressure-time record from zero to maximum pressure. At maximum pressure it is assumed that the pellets have all been consumed. For each time interval, the burning rate ($r = dx/dt$) is related to the mean pressure and rate of pressure rise over the interval.

To date only preliminary runs have been made with the burning-rate program. Based on the results of these runs, further refinement in the mechanics of the programming is indicated.

C. EMPIRICAL CORRELATION

Because of the difficulties involved in developing a "workable" theoretical igniter model (see Sections II, A and B), it was decided to attempt the development of empirical relationships as an alternate means of predicting the igniter pressurization. The main goal was to correlate the maximum pressures, $(P_C)_{\max}$, developed in the igniter over a wide range of igniter shot conditions.

Various igniter correlating parameters, and combinations of parameters, were tried on the basis that the pressurization of the igniter would display characteristics of both rocket and closed-bomb internal ballistics. The best correlation found was:

$$(P_C)_{\max} = B(K\Lambda)^b \quad (12)$$

where K is equal to S_o/A_t , the ratio of the initial pellet area to the nozzle throat area

Λ is equal to $M_o/(V_F)_o$, the ratio of total pellet weight to the free volume of the igniter (chamber volume minus initial pellet volume)

B is a coefficient, constant for a particular ignition material

b is an exponent, constant for a particular ignition material

The K factor is found in the steady-state relationship for rockets:

$$P = (a\rho_p S_o / C_D A_t) \frac{1}{1-n} \quad (13)$$

where a is the burning-rate coefficient of the propellant

n is the burning-rate exponent of the propellant

ρ_p is the propellant density

C_D is the nozzle discharge coefficient of the propellant

The Δ , or "packing-density" term, is analogous to that used in the closed-bomb work. However, in the case of the igniter, the volume of the pellets is significant compared to the igniter chamber volume.

The experimental shot data are presented according to Eq. (12) in the log-log plots of Figures 8 (M2 material), 9 (Ignition Material B) and 10 (Ignition Material C). The data of Tables 2, 3, and 4 were used to prepare these plots of $(P_c)_{max}$ vs $K\Delta$. The solid-line curve was obtained by a least-squares analysis of the data. The dashed lines represent standard errors-of-estimate limits of ± 2 from the least-squares curve; that is, 95% of the data would fall between the dashed lines for a normal Gaussian distribution.

III. DETERMINATION OF IGNITER OUTPUT

It has been mentioned that the "Hi-Lo" igniter functions as a small rocket: thermal energy is produced in the combustion chamber and, as the reaction products are expanded through the nozzle, some of the thermal energy is converted into kinetic energy. The effective use of the igniter as an ignition-energy source depends on a knowledge of the thermal and kinetic energy vented. In addition, an understanding of the nature of the flame pattern assumed by the output is desirable. This section will describe the theoretical and experimental methods used to characterize the output in terms of the following parameters:

1. The quantity and rate of MASS vented

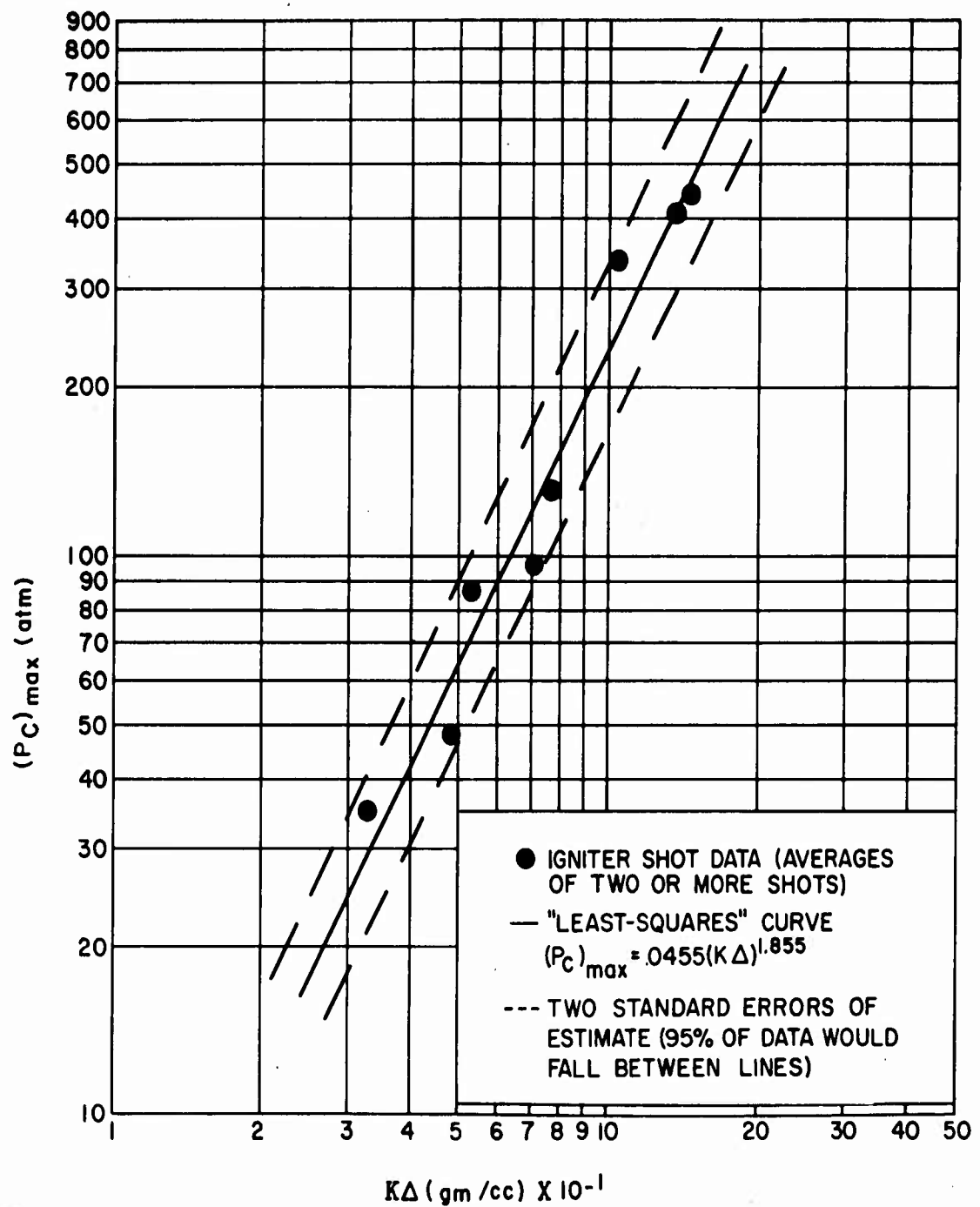


FIG. 8 A PLOT OF IGNITER MAXIMUM PRESSURE VS $K\Delta$ FOR M2 IGNITION MATERIAL

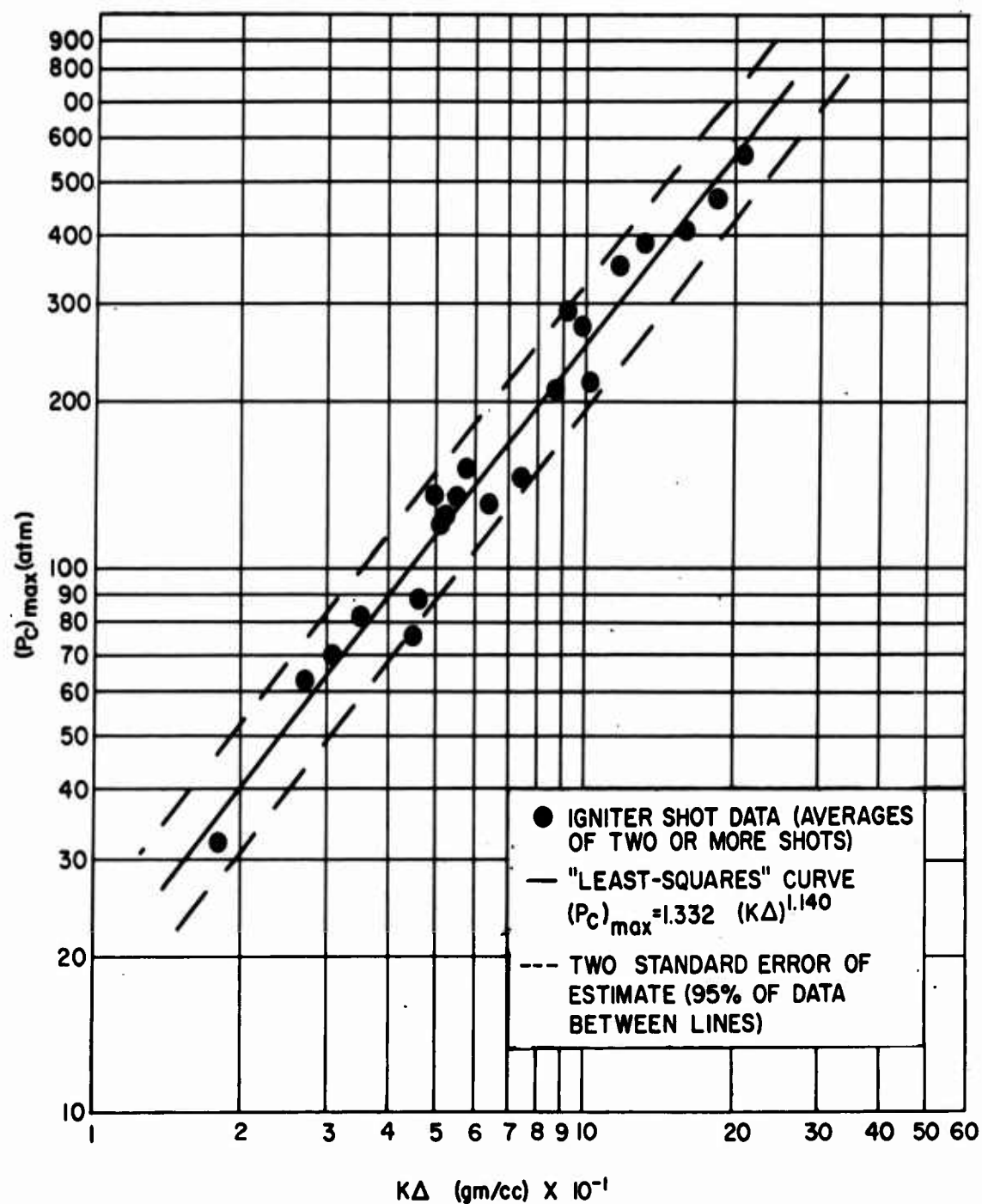


FIG. 9 A PLOT OF IGNITER MAXIMUM PRESSURE VS $K\Delta$ FOR IGNITION MATERIAL B

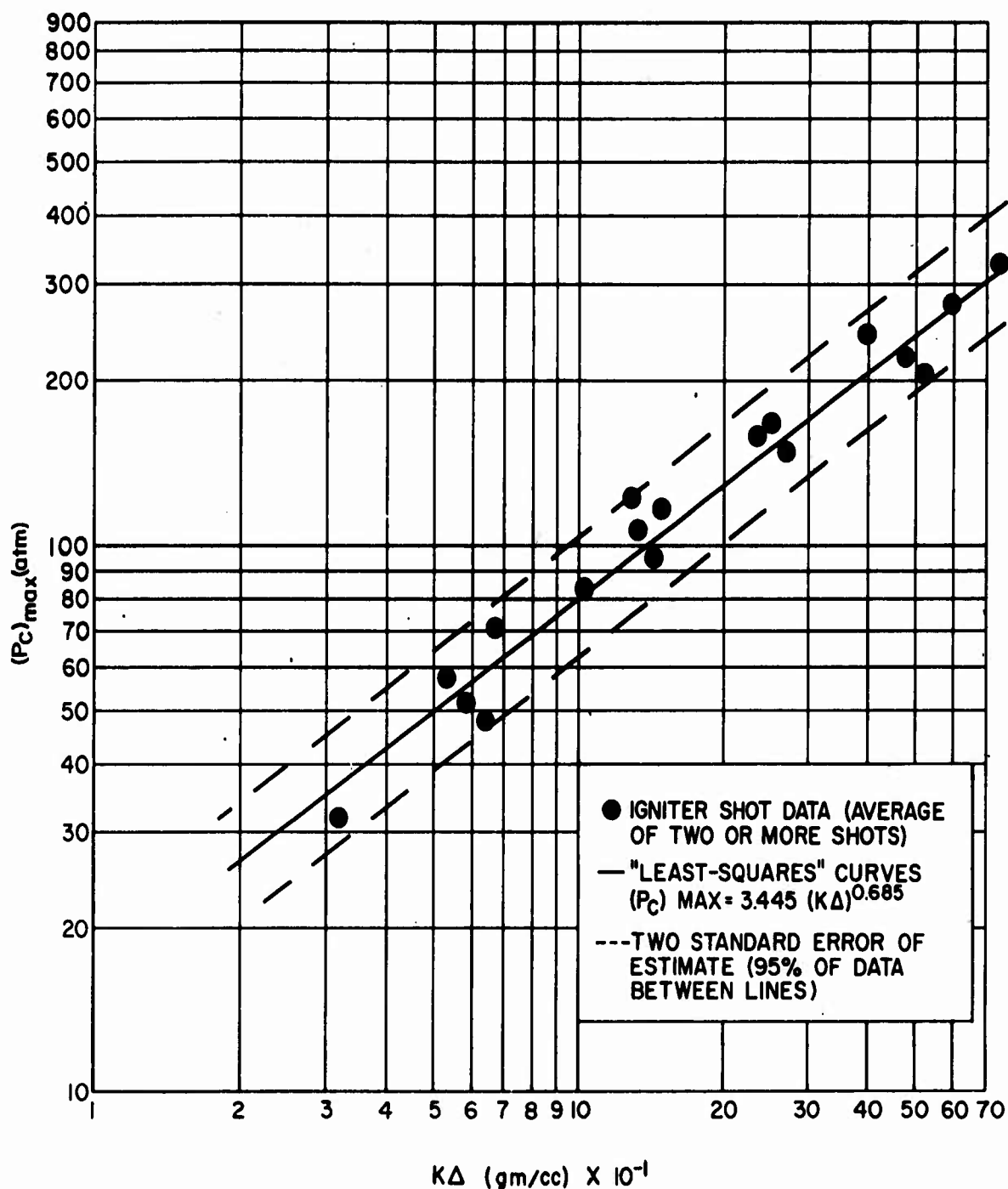


FIG. 10 A PLOT OF IGNITER MAXIMUM PRESSURE VS $K\Delta$ FOR IGNITION MATERIAL C

2. The quantity and rate of THERMAL ENERGY vented
3. The EXIT VELOCITY of gaseous and non-gaseous products
4. The FLAME PATTERN of the vented products

A. MASS OUTPUT

The characterization of the mass discharged from the igniter during a shot will be discussed in terms of the quantity vented and the rate of venting.

1. Quantity of Mass. The total quantity of mass (M_E) vented during a shot must be corrected for any loss of igniter products by deposition of the products on the igniter parts (combustion chamber, screen, nozzle). The deposited materials are in the form of solids and condensed vapors of metals and metal oxides.

In the case of Ignition Materials B and C, which produce large amounts of non-gaseous combustion products (see Table 1), a significant loss of mass can occur under some shot conditions. This was found to be as much as 30% by weighing the igniter parts before and after a shot. Therefore, an accurate prediction of M_E for shots using these ignition materials is complicated.

For M2 pellets, however, it was found that negligible weight losses occurred - as was expected. Therefore, the quantity of mass discharged during a shot is taken as the initial mass charged to the igniter (M_0) minus any gas accumulated in the combustion chamber.

2. Mass Output Rate. The mass output rate of the igniter can be determined by both theoretical and experimental methods. The theoretical method makes use of the theoretical model described in Section IIA. The experimental studies consist of two parts: one, a ballistic analysis of the measured igniter pressurization; and two, an analysis of the measured pressure and temperature developed in a non-vent vessel into which the igniter is discharged. This last method serves as a "check" of the other two methods.

a. Theoretical Model

The theoretical model (Section IIA) constructed to predict the igniter pressurization can also be used to determine the

mass output rate, \dot{m}_E , during a shot. Ideally, the igniter shot condition (M_0 , K , Δ) can be fed into the computer program based on the model and the program will "print out" \dot{m}_E vs time data for the shot. The term, $C_D A_t P_C$, in Eq. (4) is directly involved in this computation.

In practice, however, the theoretical prediction of output is complicated by several factors. These have been discussed in Section II. The development of a workable theoretical model will depend on successful solution of these complications.

b. Measured Igniter Pressurization

The measured pressure-time history of an igniter shot is analyzed according to the following standard ballistic equation for large rockets:

$$\dot{m}_E = C_D A_t P_C \quad (14)$$

In this method it is assumed that venting occurs simultaneously with the first appearance of pressure in the igniter; that is, no appreciable hold-up of gases takes place prior to venting. This assumption has been verified in studies made to compare the response times of two synchronized pressure probes; one in the igniter and the other in a short, non-vent vessel into which the igniter is vented.

Some typical results obtained with the use of this method are given in Fig. 11 for M2 shots. Plotted are the \dot{m}_E vs time histories for a number of shots of different KA values. A mean value of C_D , obtained by the method described in Section II B1 was used to make the calculations.

The determination of reliable \dot{m}_E data by this method depends mainly on two factors: (1) no deposition of igniter-product mass on the igniter parts, and (2) an accurate value of C_D and little or no deviation from the C_D value throughout the shot. In the case of M2 material, the first criteria is met (see Section III A1). Studies involving the second factor are described in Section II B2.

c. Pressurization of a Non-Vent Vessel

An experimental method is being developed to serve as a check of the output rates predicted by the theoretical and analytical techniques (described above). In this method

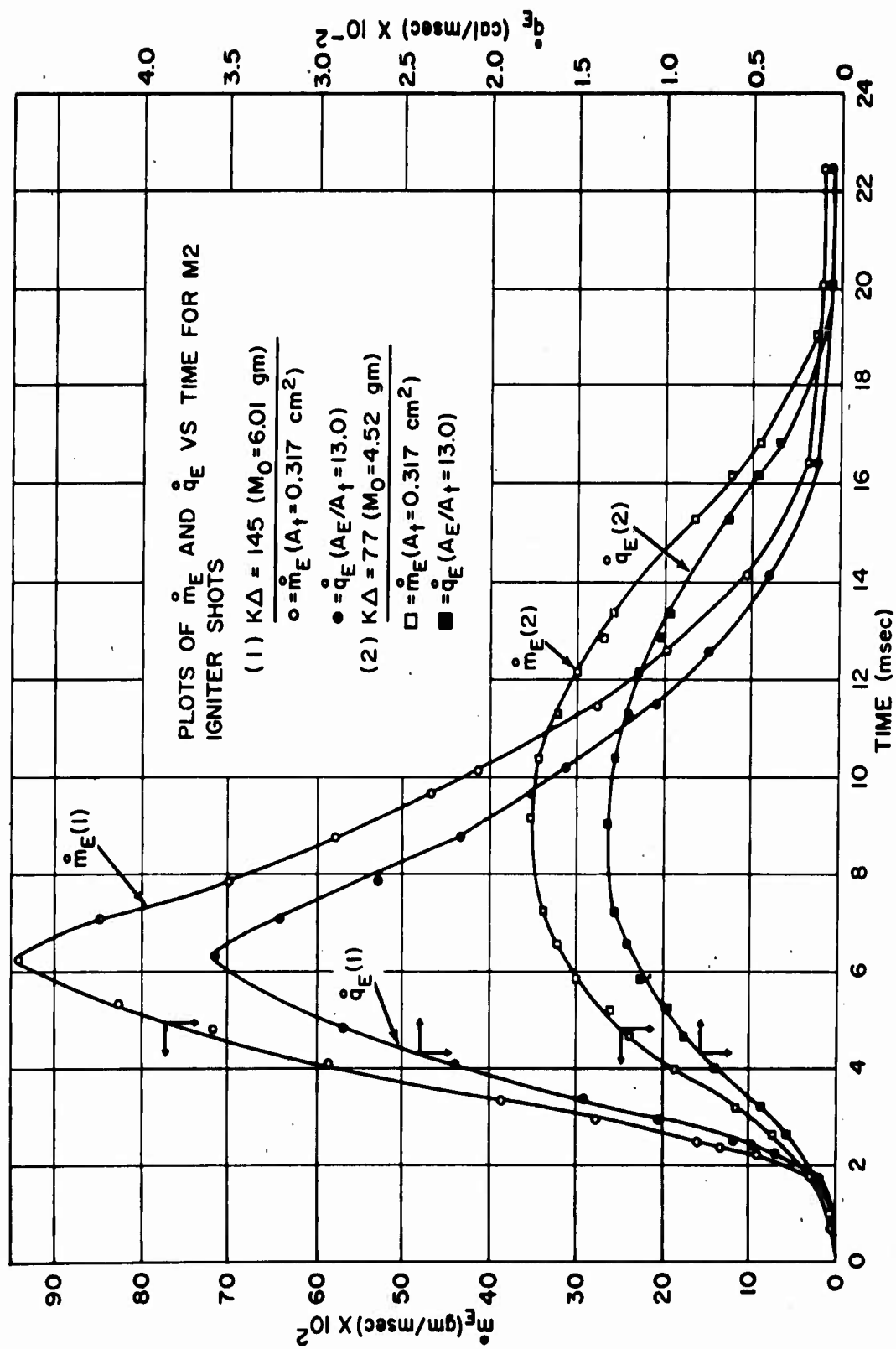


FIG. 11 A PLOT OF MASS AND THERMAL-ENERGY OUTPUT RATES FOR IGNITER SHOTS USING M2 IGNITION MATERIAL

the output rate is calculated from the measured pressure and temperature developed in a closed vessel into which the igniter is vented. The metal motor casing from the NOL research rocket (10.2 cm ID) was converted into a closed vessel by "plugging" the nozzle end. As the igniter vents into the vessel, the pressure and temperature of the output in the vessel are continuously monitored with fast response pressure probes and thermocouples placed at the inside-wall surface of the vessel. The apparatus used is pictured in Fig. 12.

The pump shown in the photograph was used to pull a 0.03 atm (0.9 in.) vacuum on the vessel prior to firing the igniter. The reduced air content minimizes oxidation and thermal-mixing effects between air and the igniter output that can complicate the interpretation of the pressure and temperature measured in the vessel. In the initial design of the apparatus, all parts of the vessel exposed to the igniter gases were covered with a thin sheet of plexiglass to reduce heat losses to the walls. An effort was made to minimize the amount of heat-transfer surface exposed to the gases; however, it was realized that if the vessel is made too small, the high pressures developed in the vessel would perturb the igniter pressurization. Such perturbations would be most likely to occur toward the end of the venting process when the igniter pressure is rapidly approaching atmospheric pressure and the vessel pressure is nearing its maximum value.

A typical record (recording oscillograph) for a non-vent motor shot is shown in Fig. 13. Pressure probes were placed in the fore and aft ends of the vessel and in the fore end of the igniter combustion chamber. In this shot, two fast-response thermocouples were positioned about half way between the front and back of the vessel.

The analysis of the transient pressure and surface-temperature data for a shot consists of two steps: (1) conversion of the surface-temperature data to static gas temperatures and (2) conversion of the gas pressures and temperatures to igniter output-rate data. A detailed description of the technique used to convert surface temperatures to static gas temperatures will be covered in another technical report. Briefly, two thermocouples are placed at the inner surface of the vessel walls at the same axial position from the igniter but at slightly different radial positions (approx. 30°). Thus, both thermocouples "see" effectively the same heat-transfer coefficient and adiabatic wall temperature. The thermocouples used are manufactured by NANMAC Corp. (9). They consist of two thin ribbons of iron and constantan electrically insulated from each other by thin sheets of mica and potted in a base (matrix)

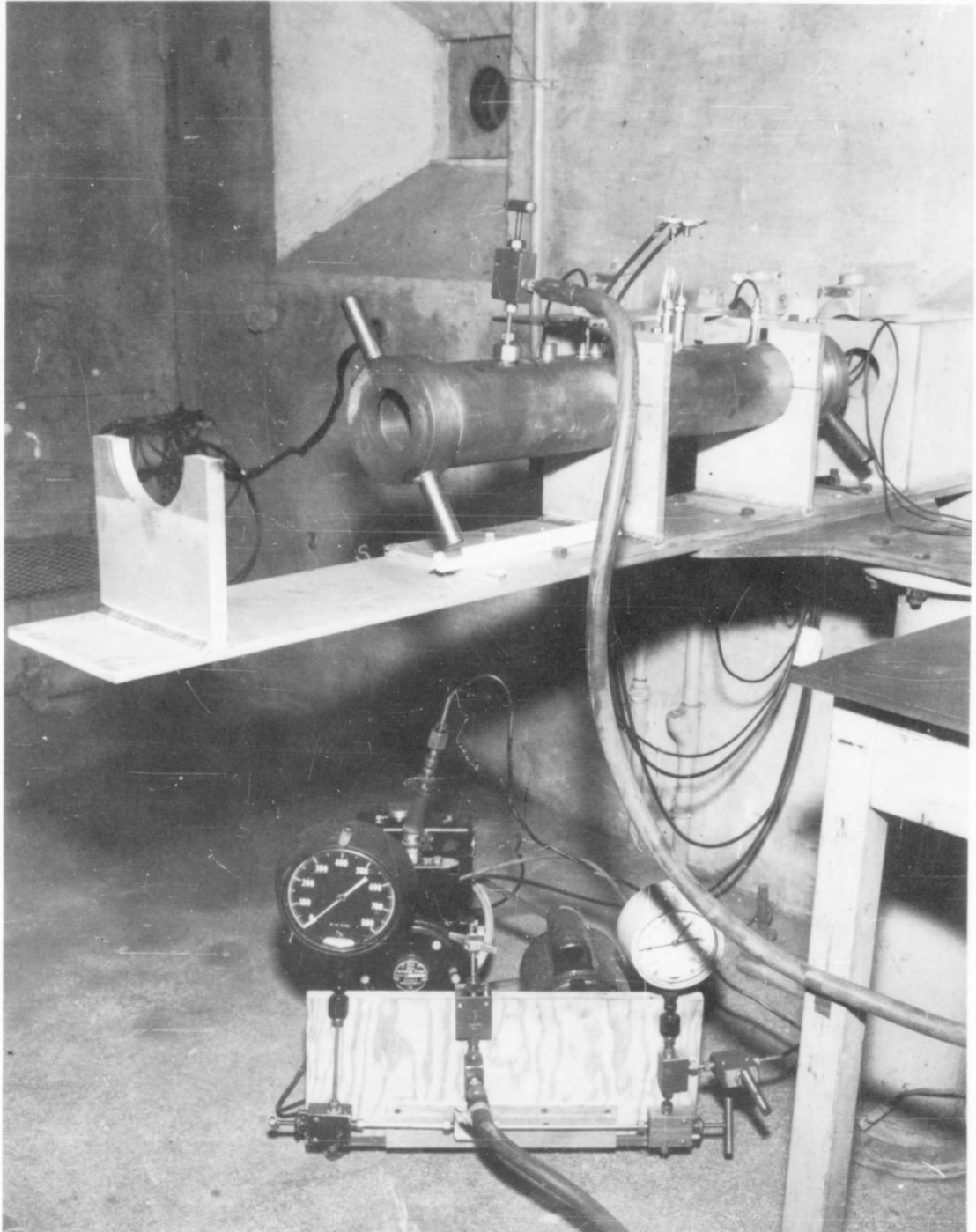


FIG. 12 A PHOTOGRAPH OF THE NON-VENT VESSEL

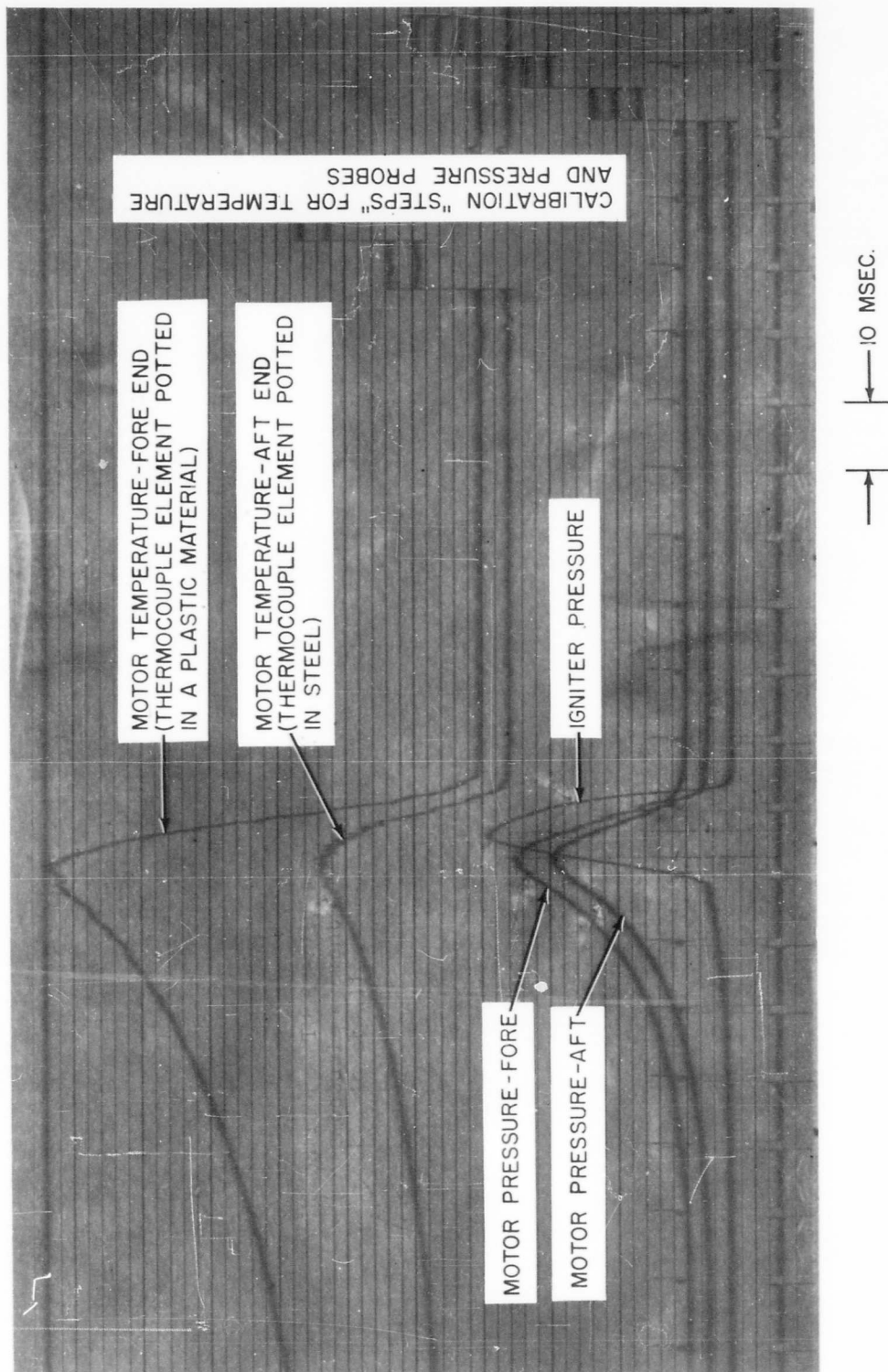


FIG. 13 A TYPICAL PRESSURE- AND TEMPERATURE-TIME RECORD FOR A NON-VENT VESSEL SHOT

material. For this study, different thermal-property matrix materials are used for each thermocouple resulting in different energy-absorption and surface-temperature characteristics. The surface-temperatures obtained from each thermocouple for a shot are first used to determine the rate of energy absorbed by the matrix materials. These data, in combination with the surface temperature, are then used to calculate the adiabatic wall temperature and the static temperature of the igniter gas.

Given the static temperature and pressure of the gas in the vessel during a shot, the mass contained in the vessel at any time, $m(t)$, can be determined from the ideal gas law and the molecular weight of the igniter products.

$$m(t) = (P_g/T_g)(M.W. \times V/R) \quad (15)$$

where P_g is the measured static gas pressure in the vessel

T_g is the calculated static gas temperature

V is the vessel volume

$M.W.$ is the molecular weight of the gas

R is the ideal gas constant

The value of $m(t)$ at the maximum vessel pressure (end of venting) should be equal to the weight charged to the igniter, M_0 , provided mass is not lost in the igniter. Assuming ideal and instantaneous mixing of the igniter output with the previously vented gases, the change in mass, Δm , in the vessel over small time increments ($\tau = 1.0$ millisecc) is equal to the rate of mass output, \dot{m}_E , from the igniter. That is:

$$\dot{m}_E(t) = \frac{\Delta m}{\tau} = \frac{m(t+\tau) - m(t)}{\tau} \quad (16)$$

The end result of the analysis is a plot of \dot{m}_E vs time. These data are independent of the heat losses or any other non-ideal internal ballistics that might occur in the igniter. The main sources of error in the technique will probably be in the determination of the static gas temperature and in the assumption that instantaneous mixing of gases occur in the vessel.

B. OUTPUT OF THERMAL ENERGY

1. General. Data on the thermal energy vented from the igniter during a shot can be determined from a thermodynamic

analysis of the production and expansion of combustion products in the igniter. The thermal-energy characteristics of the products at vented conditions can be expressed in terms of an "enthalpy" value. In the general case, this enthalpy will depend on the thermodynamic properties of the products at the exit conditions of the nozzle - that is:

$$h_E = f(c_p, T_E, P_E) \quad (17)$$

where h_E is the specific enthalpy of the output

c_p is the average heat capacity at constant pressure of the output

T_E is the temperature of the output (at the nozzle exit plane)

P_E is the pressure of the output

For an all-gaseous igniter output ("one-phase"), a simplified version of Eq. (17) can be used to obtain fairly accurate values of h_E . This involves the following assumptions: (1) ideal gas behavior of the igniter products (ideal caloric and gaseous equations of state); (2) isentropic nozzle expansion; (3) constant composition of the flowing fluid ("frozen flow"); and (4) "full-flow" in the igniter nozzle; i.e., no separation of the fluid from the nozzle walls.

In the case of an igniter output containing large amounts of non-gaseous materials (e.g., products of Ignition Materials B and C), an exact computation of the enthalpy is quite complex. For example, some of the factors that must be considered are: (1) thermal and velocity lags between gases and non-gases in the fluid; (2) deposition of combustion products inside the igniter; (3) phase changes; and (4) non-ideality of the igniter products.

Because of the above complications, the discussion of methods used to determine the quantity and rate of thermal energy vented from the igniter will be restricted to one-phase outputs (e.g., M2 products). The determination of these parameters involves an analysis of the specific enthalpy based on the temperature and specific heat of the igniter products.

a. Specific Enthalpy

The specific enthalpy of the igniter output can be determined from the change in enthalpy of the combustion products

that occur between the entrance and exit of the igniter nozzle. If it is assumed that the products behave as perfect gases and are also calorifically ideal (i.e., if the product heat capacity does not change with temperature or pressure) the enthalpy change may be expressed as follows:

$$h_C - h_E = c_p(T_C - T_E) \quad (18)$$

where h_C is the specific enthalpy of the products in the combustion chamber

h_E is the specific enthalpy at nozzle exit conditions

T_C is the combustion-chamber pressure of the products

Also

$$h_C = c_p(T_C - T_b) \quad (19)$$

$$h_E = c_p(T_E - T_b) \quad (20)$$

where T_b is the base or standard temperature = 25°C.

The assumption that the c_p for the M2 products is effectively independent of pressure and temperature appears to be reasonable. For example, it has been reported (20) that the gaseous c_p for JPN (a double-base composition similar to that of M2) is essentially constant over a temperature range of from 1600 to 2800°C and a pressure range of from 1 to almost 700 atms.

b. Fluid Temperatures

For a perfect gas undergoing ideal expansion, the temperature at the end of the expansion can be computed from the following relationship:

$$T_E = T_C(P_E/P_C)^{\frac{\gamma - 1}{\gamma}} \quad (21)$$

where γ is the specific heat ratio of the igniter products

P_C is the chamber pressure of the igniter

To further simplify Eq. (21) it can be assumed that T_C remains constant during a shot, i.e., does not change appreciably from its isobaric value. This assumption was verified by calculating the change in the T_C that would result if the reaction

products were isentropically expanded between the chamber free volume prior to pellet ignition and the chamber volume at "burn-out" of the pellets. For typical packing densities (weight of pellets/initial igniter free volume), it was found that T_C would vary by only 2 or 3% during a shot.

If it is assumed that the nozzle "flows-full" throughout the shot, then the ratio P_E/P_C should remain constant during the shot. Since T_C is effectively constant, this means that for a given nozzle expansion ratio, T_E also remains constant during the shot.

2. Quantity of Thermal Energy. The quantity of thermal energy discharged, q_E , in a shot using M2 material can be determined from the following relationship:

$$q_E = M_E h_E \quad (22)$$

where M_E is the total quantity of igniter mass discharged during the shot.

The determination of M_E is described in the previous section (III A1). For M2 material it was shown that c_p , T_E and T_C are essentially constant during a shot. It follows that h_E must also remain constant during the shot. Therefore, from Equations (19) and (20)

$$h_E \approx h_C(T_E - T_b)/(T_C - T_b) \approx \text{constant} \quad (23)$$

3. Thermal-Energy Output Rate. The rate at which thermal energy is vented, \dot{q}_E , during a M2 shot can be determined from data on the mass output rate and a differential form of Eq. (22).

$$\dot{q}_E = (dq/dt)_E = \dot{m}_E \cdot h_E \quad (24)$$

where \dot{m}_E is the mass output rate for the shot.

The determination of \dot{m}_E was discussed in Section III A2. Values of \dot{q}_E for each \dot{m}_E can be computed from the specific enthalpy of the shot determined from Eq. (23).

Values of \dot{q}_E calculated from Eq. (24) for some typical M2 shots are given in Fig. 11. The \dot{m}_E data was obtained with

the use of the method described under Section III A2b.

C. EXIT VELOCITY

Ideally, the exit velocity, v_E , for a DeLaval rocket nozzle can be determined from the standard ballistic equations:

$$v_E = \left\{ \frac{2\gamma}{\gamma-1} \frac{R}{MW} T_c \left[1 - (P_E/P_c)^{\gamma-1/\gamma} \right] \right\}^{\frac{1}{2}} \quad (23)$$

where

γ is the specific heat ratio

M.W. is the average molecular weight of the igniter products

T_c is the adiabatic, isobaric flame temperature of the products

R is the universal gas constant

P_c is the igniter chamber pressure

P_E is the nozzle exit pressure

The ratio P_E/P_c is completely determined when the nozzle expansion ratio, A_E/A_t (exit-to-throat area), and γ are fixed.

Eq. (23) is based on the assumptions that the fluid is of constant chemical composition throughout the expansion process, that the fluid behaves as a perfect gas, that the expansion process is isentropic and that the igniter nozzle is "flowing full".

For an ignition material such as M2 that produces only gaseous combustion products, the use of Eq. (23) is justified. However, when evaluating compositions such as Ignition Materials B and C that produce non-gaseous products, the determination of exit velocities becomes more complicated. For this reason, empirical as well as analytical methods were adopted to evaluate the exit velocity for these materials.

1. Gas Exit Velocity. Standard ballistic relationships can be used to calculate the exit velocity for the gaseous igniter output: the exact equation used depends on whether the igniter products also contain some non-gaseous materials.

For the nearly all-gaseous combustion products of M2 material, Eq. (23) can be used to calculate the gas exit

velocity. In the case of Ignition Materials B and C, the exit velocity for the gaseous component of the output can be approximated by the following relationship:

$$v_E = \left\{ \frac{2\bar{\gamma}}{\bar{\gamma}-1} \frac{R T_c}{MW} \left[1 - (P_E/P_C)^{\frac{\bar{\gamma}-1}{\bar{\gamma}}} \right] \right\}^{0.5} \quad (24)$$

The "bar" over γ and MW denotes that these variables are now "weighted averages" of the gases and non-gases contained in the igniter products. This equation assumes that the gaseous and non-gaseous phases are in thermodynamic equilibrium (see Section III B).

With the use of Equations (23) and (24) and standard tables for isentropic nozzle expansion (15), calculations were made of v_E over a practical range of expansion ratios (A_E/A_t). For M2 products, v_E varies from 1040 to 2840 m/sec for an expansion-ratio range of 1.0 to 101. For the gaseous products of Ignition Materials B and C, v_E varies from about 1600 to 2000 m/sec for an expansion range from 7.5 to 101.

2. Exit Velocity of Non-Gaseous Products. The determination of the exit velocity for the non-gaseous (liquids and solids) materials in an expanding fluid is complicated by the fact that the gases and non-gases are usually not in velocity equilibrium. Under these conditions, an analytical treatment of the non-gas velocity similar to that used for the gas velocities is prohibitively complex. For this reason, an empirical method was used to evaluate the exit velocity for the non-gaseous output of Ignition Materials B and C.

The experimental equipment used consisted of a long transparent (plexiglass) tube with an inside diameter of approximately 10.16 cm (4.0 in.). The igniter was attached to one end of the tube. The other end of the tube was open to the atmosphere; thus, the igniter products vented into the tube "saw" a constant back pressure as they moved down the tube. The movement of the igniter output past calibrated tape marks down the tube was photographed with a high-speed camera (1500 frames/sec.). The apparatus is pictured in Fig. 14. By analysis of the film, the time required to move from mark to mark on the tube was used to calculate an average longitudinal particle velocity between the calibration marks. The particle velocity at nozzle exit conditions was approximated by using the value determined a few inches downstream from the igniter. Another, more reliable,

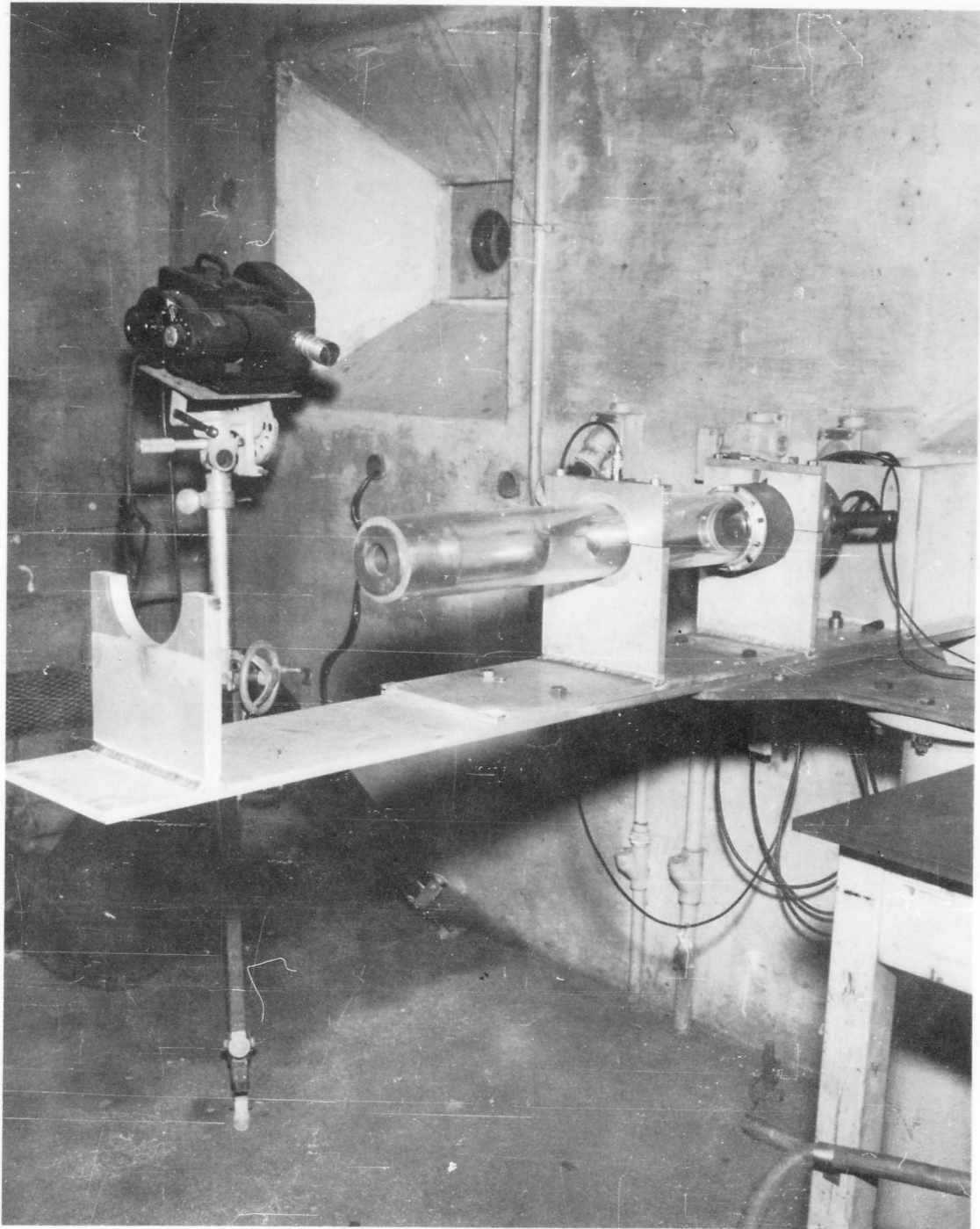


FIG. 14 A PHOTOGRAPH OF THE TRANSPARENT MOTOR AND HIGH-SPEED CAMERA

method used to determine the exit velocity was to plot the average longitudinal velocities vs the distance down-stream from the igniter and extrapolate the plot back to exit conditions. Such a plot for Ignition Materials B and C is shown in Fig. 15 for a nozzle expansion ratio of 12.3. Extrapolation of the curves resulted in an approximate exit particle velocity of 130 m/sec for both compositions.

It is interesting to note the extreme velocity lag between the particles and gases for the shots - i.e., about 120 m/sec compared to approximately 1900 m/sec for the gas exit velocities.

D. FLAME PATTERN

The pattern assumed by the igniter products as they are vented from the igniter can be of importance in determining the distribution of the products in a rocket motor. For this reason, a study was undertaken to determine the relationships between the flame pattern and the igniter shot condition for the three ignition materials and to see how much control of the pattern was possible with the present igniter design.

In this report, flame pattern is defined as the shape and hydrodynamic characteristics of the "jet" of hot gases and particles vented from an igniter nozzle. When an igniter is mated with a rocket, the igniter flame pattern characteristics will depend on many factors. Some of the more important of these are: the exit pressure, P_E , of the output (a function of the igniter chamber pressure and nozzle expansion ratio); the exit velocity, V_E , of the output (a function of igniter expansion ratio); and the back pressure, P_A , on the output. For example, the ratio of P_E to P_A will determine whether the igniter output products will be in an under-expanded, over-expanded, or normally-expanded state as they are discharged from the nozzle. Each mode of expansion results in a characteristic flame pattern: over-expansion gives a turbulent, homogeneous (with regard to temperature and gas density) jet, under-expansion gives a somewhat narrower jet consisting of a system of well-defined expansion-contraction waves and normal expansion gives a pattern that is intermediate between over-and-under expansion. The "fine details" of the jet resulting from each expansion mode is believed to be defined by such parameters as the exit velocity, exit pressure, and back pressure.

As an igniter output parameter, the flame pattern is studied from the standpoint of the various patterns that result when the igniter, at different shot conditions, is vented into an essentially constant-pressure environment. The results of this study

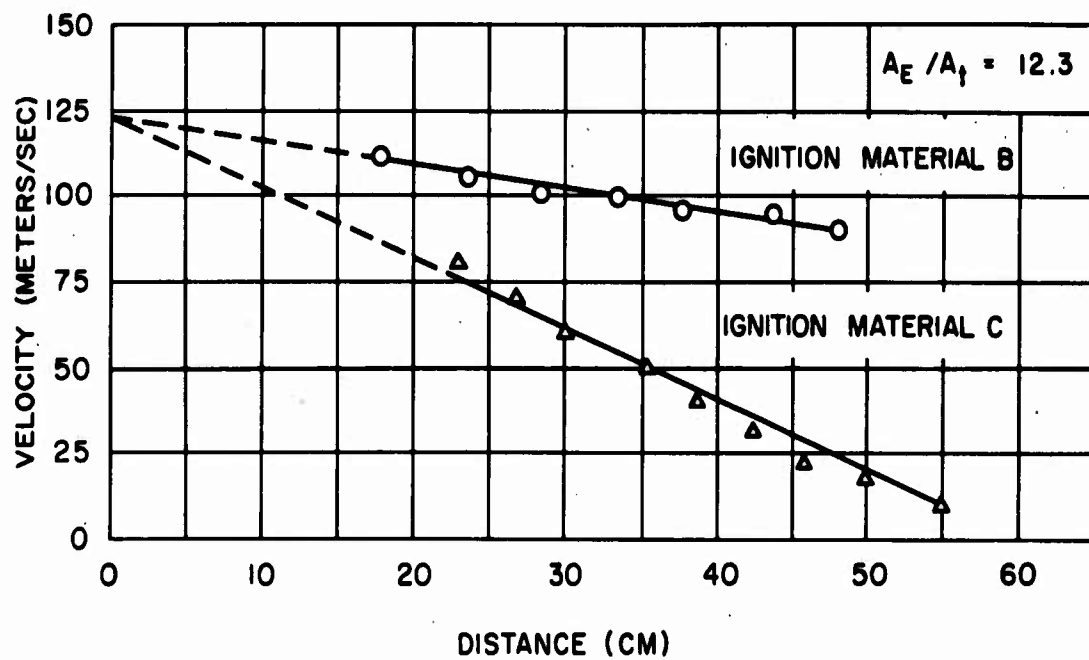


FIG. 15 A PLOT OF NON-GAS VELOCITY OF IGNITER OUTPUT VS AXIAL DISTANCE IN THE TRANSPARENT MOTOR INTO WHICH THE IGNITER IS VENTED.

will be used as a "starting point" for studying the effect on the flame pattern of a variable back pressure that occurs when the igniter discharges into a vented vessel (rocket).

The equipment used in this study was a 10.16 cm (4.0 in.) I.D. transparent (acrylic) tube, into which the igniter is vented, and a high-speed camera (see Fig. 14). The igniter shot conditions are varied through a systematic variation of K , Δ , and A_p/A_t . In addition, for some shots deflectors were placed in the divergent section of the nozzle to "spread-out" or "crimp" the flame. Pictured in Fig. 16 is the film for a shot using Ignition Material B. The film shows the build-up of the flame (left side of frame) and the movement of the flame down the transparent tube. Although not too apparent from the black-and-white copies of the color film used, the point of greatest light intensity is located at the center of the casing with gradations of intensity toward the walls. This "profile" is a result of incandescent particles diffusing through the igniter jet to the casing walls. For some shots, pressure and temperature probes were placed at the inside wall of the motor casing. These data were used to supplement that obtained from the film analyses.

IV. SUMMARY

The "Hi-Lo" igniter used in the NOL ignition studies is a small, mono-vent rocket using pelleted ignition material. Use of the igniter in scientific ignition work requires quantitative information on the physical-chemical and hydrodynamic characteristics of the igniter output. For this reason, studies have been undertaken to evaluate the output in terms of the following parameters: (1) the quantity and venting rate of the igniter-product mass discharged; (2) the quantity and venting rate of thermal energy; (3) the velocity (at nozzle exit conditions) of the vented gases and non-gases; and (4) the "flame pattern" assumed by the vented products. The ignition materials used in the study were cylindrical pellets of M2 (a double-base propellant), Ignition Material B (double-base and metal additive) and Ignition Material C (an oxidizer and metal additive).

Both theoretical and experimental techniques were used to study the output parameters. Although the original intent was to develop techniques that have general application to ignition materials of different chemical composition, emphasis was later placed on analyses of the igniter performance for an essentially all-gaseous output (M2 ignition material). It was found that the use of such a one-phase system greatly simplified the analyses of the igniter internal ballistics and output characteristics.

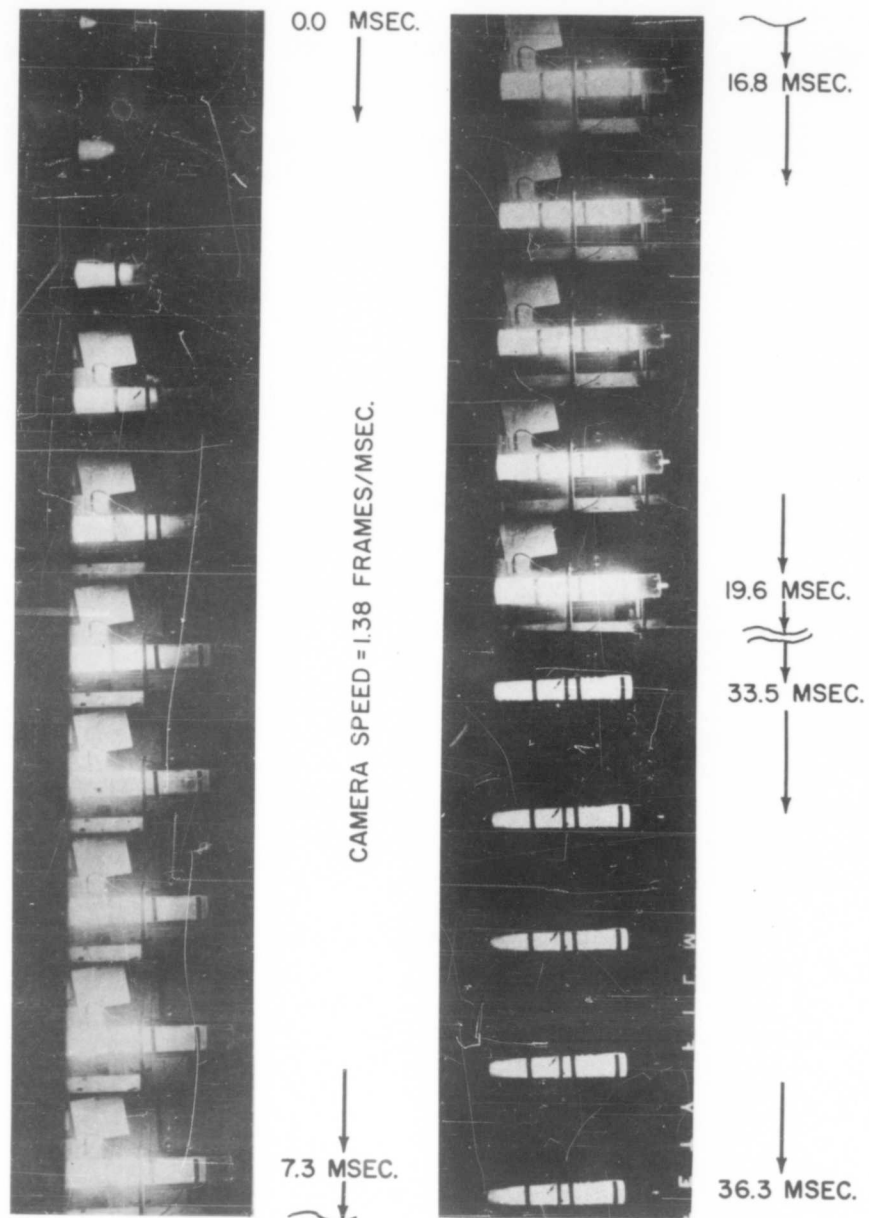


FIG. 16 A PHOTOGRAPH OF THE IGNITER OUTPUT FLAME MOVING DOWN THE TRANSPARENT MOTOR

Two main approaches were used to evaluate the igniter output: A. a study of the transient internal ballistics of the igniter and B. a study of the output as it is discharged into vented or non-vented vessels. These approaches consisted of the following:

A. Determination of the Igniter Internal Ballistics (a study of the igniter pressurization by the ignition-material combustion products).

(1) Theoretical Prediction of Igniter Pressurization.

A theoretical model was constructed to predict the pressurization of the igniter from the physical and ballistic properties of the igniter pellets and the geometry of the igniter system. Comparison of the calculated to the experimental pressures has indicated that further refinements are needed in the model to describe the completely transient pressurization occurring in the igniter.

(2) Experimental Studies of Ignition Material Ballistic and Thermodynamic Properties. To aid in the construction of a more realistic theoretical model, studies were undertaken to determine the non-ideality, if any, in the burning rate, gaseous equation of state, and the discharge coefficient of the ignition materials. The studies made use of pressure-time data from closed-bomb and igniter shots. Other studies are being made to evaluate possible changes in the discharge coefficient during a shot as a result of heat losses in the igniter combustion chamber or friction losses in the igniter nozzle.

(3) Empirical Correlation. A quasi-empirical correlation was derived which relates the maximum pressure developed in an igniter shot, for a particular ignition material, to the initial weight and burning surface of the ignition material, the free volume of the igniter combustion chamber and the igniter nozzle throat area.

B. Determination of Igniter Output

(1) Mass Output. It was found that any determination of the quantity of output mass must take into account mass losses inside the igniter for shots involving Ignition Materials B and C.

Three methods were studied as means of determining the mass output rate of the igniter. The first method made use of the theoretical model constructed to predict the igniter pressurization. The second method made use of a ballistic analysis of the

measured igniter pressurization; that is, rate = discharge coefficient x throat area x igniter pressure. The third method was based on the measurement of temperature and pressure in a non-vent vessel into which the igniter is vented.

(2) Thermal Energy Output. The quantity and venting rate of thermal energy was determined from an analysis of the production of thermal energy in the igniter combustion chamber and the conversion of thermal to kinetic energy during the isentropic expansion of the combustion products in the igniter nozzle.

(3) Exit Velocity. The exit velocity of gaseous output was calculated using standard ballistic equations for nozzle flow. The non-gas velocity (solids and condensed liquids) was determined from a photographic study of the igniter products as they are vented into a transparent motor casing. Significant velocity "lag" between the gases and non-gases for the output of Ignition Materials B and C was noted.

(4) Flame Pattern. The flame pattern of the igniter output (the geometry and expansion characteristics of the output jet) was studied with the use of a high-speed camera. Significant variation of the flame pattern with the shot condition was observed.

Most of the data processing and many of the analytical methods described in this report have been coded for solution on an IBM digital computer.

V. FUTURE WORK AND RECOMMENDATIONS

Listed below are the plans for future igniter evaluation work by NOL and the recommendations for further igniter studies by other groups. In general, the NOL group will emphasize those methods of evaluating igniter performance that offer the most direct and expeditious means of obtaining reasonably accurate output data. The experimental and analytical work will only involve the use of M2 ignition material.

A. Determination of Igniter Internal Ballistics

(1) Theoretical Prediction of Igniter Pressurization. No further work on the theoretical model to predict igniter pressurization is planned. The next steps in the development of the model would have included a "check-out" study using M2 shot data and suitable modifications of the model based on the results of the studies of the ignition material properties (see

Section II B).

(2) Experimental Studies of Ignition Material Ballistic and Thermodynamic Properties. It is planned to continue the study of the discharge coefficient and, in particular, the variation of the coefficient during the M2 shots. The success of this study will depend on the successful development of a temperature-energy program to determine gas temperatures in the non-vent vessel (see Section IIB).

No further closed-bomb studies are planned to determine gaseous equations of state or burning rates. In order to make the bomb programs operational, more work is needed to determine the best means of minimizing and correcting for heat losses in the bomb.

(3) Empirical Correlation. Correlation of igniter shot data for "new" M2 material will be made using the $K\Delta$ relationship (Eq. (12)). The newly-manufactured M2 consists of four different sizes of cylindrical pellets.

Another useful empirical characterization of the igniter shot data would be a correlation to predict the igniter pressurization times; i.e., the time to maximum pressure.

B. Determination of Igniter Output

(1) Mass Output

a. Quantity of Mass. A useful area of study would be a quantitative analysis of the "mass-loss" problem for ignition materials producing non-gaseous products. For example, a trend was noted between the product mass lost in the igniter and the maximum igniter pressure in the case of shots using Ignition Materials B and C.

b. Mass Output Rate. Emphasis will be placed on the determination of output-rate data based on a ballistic analysis of the measured igniter pressurization. This method will be supplemented by the results of the studies on the pressurization of a non-vent vessel into which the igniter is vented.

(2) Output of Thermal Energy

a. Quantity and Venting Rate of Thermal Energy. Calculation of the thermal energy output for all M2 shots will be made. Energy-rate determinations will make use of the mass

rate data determined from the ballistic analysis of the igniter pressurization.

(3) Exit Velocity

a. Gas Exit Velocity. Calculation of the exit velocities of all M2 shots will be made.

b. Non-Gas Exit Velocity. No further study of non-gas velocities is planned. An interesting study would be an empirical correlation of the non-gas exit velocity in terms of the igniter shot conditions and the physical-chemical properties of the non-gases (e.g., particle size, solid-to-gas ratio).

(4) Flame Pattern

a. Shots will be made to further characterize the flame pattern of M2 products at different shot conditions in air and in a vented vessel.

b. Further study would be desirable to relate the flame pattern characteristics to the igniter ballistic and output parameters; i.e., the igniter exit velocity and pressure (at a given igniter chamber pressure).

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REFERENCES

1. Altman, D., "The Characteristics of Gasless Igniters", Bull. 2nd JANAF Ad Hoc Ignitability Panel Meeting, Oct. 1956 (Conf.).
2. Beauregard, R. L., Harrell, B. W., and Kendall, P., "Solid-Propellant Rocket Ignition Systems. III. Electronic Instrumentation Used in the NOL Ignition Research Program, NOLTR 62-110, 26 June 1962.
3. Beyer, R. B. and Fishman, N., "Solid Propellant Ignition Studies with High Flux Radiation Energy as a Thermal Source", Progress in Astronautics and Rocketry, Vol. 1, Paper No. 30, Academic Press Inc., N. Y., 1960.
4. Bickford, H. G., Conant, L. C., and Wachtell, G. P., "Study of Ignition by Radiation and Natural Convection in Confined Atmospheres, Bull. 1st Symp. on Solid Propellant, p. 87. (Conf.).
5. Bryan, G. J. and Enig, J. W., "Ignition of Propellants by Hot Gases, Part II. Ignitability Comparisons of Twelve Propellants and Some Effects of Shape on Ignitability, NOL NAVORD 3703, Dec. 1954 (Conf.).
6. Churchill, S. W., Kruggel, R. W. and Brien, J. C., "Ignition of Solid Propellants by Forced Convection", A.I.Ch.E. Journal, p. 568, Dec. 1956.
7. Enig, J. W., "Ignition Energies of Solid Propellants", NOL NAVORD 3748, 1954 (Conf.).
8. Goldhagen, S., Wiegand, J. H., "Estimation of the Alclo Requirements for Igniters", Bull. of the 4th JANAF Ad Hoc Ignitability Panel Meeting, May 1960 (Conf.).
9. Hull, S., "High Speed Thermocouples", Missile Design and Development, June 1960.
10. Johns Hopkins Applied Physics Laboratory, "Propellant Manual SPIA/M2", Unit No. 31 (Conf.).
11. Kreidler, J. W., "Double-Base Solid Propellant Ignition", Bull. of the 4th JANAF Ad Hoc Ignitability Panel Meeting, May 1960 (Conf.).

REFERENCES (Cont'd)

12. Larrick, B. F., Beauregard, R. L., Zovko, C. T. and Amster, A. B., "Rocket Motor Ignition Systems. I. A Rocket for Studying the Variables Affecting Pressure During Ignition", NOL NAVORD 6851, 1960 (Conf.).
13. Larrick, B. F., "Two New Ignition Materials", NOL NAVORD 6650, Feb. 1960 (Conf.).
14. McAlevy, R. F., Cowan, P. L., and Summerfield, M., "The Mechanism of Ignition of Composite Solid Propellants by Hot Gases", Paper Presented at ARS Conference, Princeton, N. J., Jan. 1960.
15. Seifert, H. S., and Crum, J., "Thrust Coefficient and Expansion Ratio Tables", Space Technology Laboratories, Feb. 1956.
16. Sharn, C. F., Beauregard, R. L., Ferguson, J. D., Harrell, B. W. and Zovko, C. T., "Current Status of the Solid-Propellant Ignition Program at NOL", NOL NAVWEPS 7287, 1960 (Conf.).
17. Sharn, C. F., "Solid-Propellant Rocket Ignition Systems II. A Research Program for the Scientific Design of Igniters", NOLTR 61-110, Oct. 1961.
18. Sternberg, H. M., "Heat Loss Corrections in the Determination of the Force and Linear Burning Rate of Propellants by Closed Bomb Methods", NOLTN 2166, June 1955 (Conf.).
19. Warren, F. A., Carlton, C. H., and Wiegand, J. H., "Studies in Ignition", Southwest Research Institute Tech. Rept. No.7, Aug. 1955 (Conf.).
20. Wimpres, R. N., "Internal Ballistics of Solid-Fuel Rockets", p. 14, McGraw-Hill Book Co., N. Y., 1950.
21. Wise, J. S., "On a Mechanism and Explanation of Burning Rate in Radial Burning Motors", Bull. 15th JANAF Meeting, Vol. VI, p. 119, June 1959 (Conf.).
22. Zovko, C. T., "Stability of Several Ignition Materials", Bull. 4th JANAF Solid Propellant Surveillance Panel, Dec. 1959 (Conf.).
23. Zovko, C. T., "Igniter Burning Rate Calculations", Bull. 4th JANAF Ignitability Panel Meeting, p. 239, May 1960 (Conf.).

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